Tall Timber in Denver: An Exploration of New Forms in Large Scale Timber Architecture

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TALL TIMBER IN DENVER:
AN EXPLORATION OF NEW FORMS IN LARGE SCALE TIMBER ARCHITECTURE

A Thesis Presented

by

Andrew Peter Weuling

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ABSTRACT

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Wood has been utilized by humans for thousands of years in the construction of our built environment. More recently, our expanded understanding of the material and the advancement of engineered wood have allowed us to use wood like never before. Concrete and steel, however, have emerged as the main materials used in large scale construction in the late 19th and 20th Centuries. As we are battling and searching for solutions to climate change, the importance of wood in large scale construction has increased as not only is its carbon intensity is lower than steel and concrete, but its existence stems from sequestered carbon. Yet as timber finds its way into large-scale projects, the forms it takes resemble those of concrete construction. Although this form is functional, it does not take full advantage of its capabilities or mitigate the weaknesses of wood.

This thesis is concerned with exploring new options for mass timber, finding forms more appropriate to wood's mechanical and aesthetic properties. Research began with precedent studies of existing mass timber structures to see which strategies would be useful in the project. Next a theoretical project was undertaken to design an 18-story

timber-based high rise in Denver, Colorado. The design uses a variety of Engineered Wood Products (EWP) in the most effective and efficient way.

The findings of this study have shown that wood, being an isotropic material, prefers to have forces run parallel to its grain. Combining multiple types of engineered wood arranged to create forces travelling parallel to their fiber grain direction created a system that was efficient, strong, and architecturally effective. The design also works to avoid subjecting wood to forces perpendicular to its wood grain, thus avoiding its weaknesses. Finally, the design uses common, stock, engineered lumber products to make the project more economical. It produced a high rise design that serves as a highly desirable model for future projects across the United States and world. This technology will not be limited to high rises and can be used in a plethora of large-scale building types. Broader implementation of this technology will help to decrease our species' carbon footprint as our population expands and builds. More material efficient structural solutions will encourage wider spread implementation and their aesthetic qualities will increase their desirability by private and government investors alike.

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THE LANGUAGE OF TIMBER

1.1 Introduction

> *Louis Kahn used to tell his students: if you are ever stuck for inspiration, ask your materials for advice. "You say to a brick, 'What do you want, brick?' And brick says to you, 'I like an arch.' And you say to brick, 'Look, I want one, too, but arches are expensive and I can use a concrete lintel.' And then you say: 'What do you think of that, brick?' Brick says: 'I like an arch.'"*- Wainwright, 2013

Materiality and expression of materiality is as important now as it was in the mid-20th century when Louis Kahn taught this lesson to his students. Kahn and his contemporaries found themselves in a new age of building technology with an expanded universe of forms now possible. Kahn's brick question dealt the brick's use as a unit; however, it inspired this thesis's more abstract question: How does a material itself want to be used? Kahn explored other materials like concrete, a non-unit material, and held the same regard for the materials needs and wants in his architecture. Nowadays there are even more building products to choose from than 50 years ago. An architect in the early 21st century has a wide assortment of materials at their disposal. They have the enormous task of placing these new materials where they are best suited. One of the most important emerging materials used in architecture is an "oldtimer" among building materials: an improved version of wood, engineered lumber. Exciting technology such as cross laminated timber promises to revolutionize the built landscape. Whereas wood was once limited to small structures, these new high strength materials open the doors to massive wooden structures. Being a highly sustainable material in a world threatened by climate change it is easy to see where the demand to execute large, and typically high impact, structures in wood comes from. However, as with the advent of iron and concrete construction, architects are now tasked with discovering the language mass timber speaks. What does a stick want?

This thesis will explore the design language of timber architecture by allowing the material's needs to guide the design process of a theoretical project. Rather than designing a form and forcing the material to comply the structural, tectonic, and aesthetic properties of wood will guide the form. As with all buildings, the needs of the program must not be ignored. Therefore, the design process will not create a form and force fit a program into it, rather the program and the needs of timber will work in harmony to develop the building form.

The project will construct an 18-story mixed use residential/commercial tower in the heart of Denver, Colorado. A residential program is well suited to a building whose material is associated with healthy living. The program is very flexible making a tectonic balance an easier goal. The city of Denver has been chosen due to its persistent growth, adventurous spirit of the city and its inhabitants' interest in sustainability. This adventurous spirit is expressed dramatically with the integration of a climbing gym at the heart of its structure. The site itself is a parking lot in the heart of downtown with great potential to become a joyful location to live within. The building promotes an environmental commute and transportation lifestyle allowing direct access to the river bike and foot path, which expands throughout the metropolitan area. The first floor will offer commercial spaces and turn a stagnant parking lot into a thriving economic hub. The site offers excellent access to culture, work, and outdoor recreation.

This majority of the building material weight will be determined by timber. Wood structural systems that will be explored include diagrid structures, post and beam, CLT (Cross Laminated Timber), and steel hybrid systems. Structural design will remain schematic in its level of detail with member sizes approximated given that this thesis is not based on civil engineering. The building aesthetically will be designed to showcase and celebrate its materiality. Wood will be shown where possible. However, this structure will need to be adequately protected from fire and moisture. This building will be designed to be a convincing proposal to code officials with the intention being that it can inspire change in the United States' strict code to mirror more progressive codes such as those found in Europe and Canada. This thesis hopes to inspire architects to advocate mass timber to their clients and provide effective ideas that will progress the field of mass timber architecture.

1.2 Background

The 21st century marks the beginning of a new technological age for humanity. Since the 1920's our species has explored every corner of earth, eliminated horrific diseases, gained the ability to instantaneously communicate across oceans, and have even walked on our moon.

Unsurprisingly these last 100 years have seen significant technological growth in the field of architecture. In 1920, the world's tallest building was the Woolworth Building in New York City standing at 792 ft (241m). The Woolworth Building would hold this record for another decade. As the century went on, the record was constantly broken as technology allowed buildings to grow by hundred foot leaps every year. In 2021, having held the record for over a decade, the world's tallest building is the Burj

Khalifa located in Dubai. The Burj Khalifa stands at 2,717 ft (828m), nearly 3 ½ times higher than its 100-year-old counterpart. Our construction methods have changed significantly as well. In the 1920s, much of our larger structures were being executed in heavy masonry, with the steel frame slowly gaining popularity. Fast forward to now and one would be hard-pressed to find a project in the first world that used stone as a primary construction element. The steel frame and its later counterpart, reinforced concrete, have dominated the large-scale construction sector for decades. The two systems are tried and true and are well known by architects and builders alike.

Concrete and steel, given their high strength, unlocked a world of long clear spans and lighter facades for architects. Technology freed architects to explore new forms and scales never before possible and, as to be expected, they took full advantage. However, in the 21st century, we have learned of the consequences of this exuberance. The energy source humanity chose for the 20th century has doomed it in the 21st century, fossil fuels. Our voracious appetite for burning fossil fuels blinded us to the effects of their byproduct, greenhouse gasses. Greenhouse gasses, such as CO_2, permeate our atmosphere at levels high enough to trap heat that otherwise would radiate into space. This trapped heat is now raising global average temperatures and wreaking havoc on our ecosystems, weather, and sea levels. To date, 41% of our energy consumption worldwide is due in part to our built environment (Dederich, 2019, 14) including heating, cooling, lighting, construction, demolition, and material production. A great deal of energy is involved in construction alone, with large machinery required to excavate sites and transport materials. Concrete and steel, while strong, are high weight materials and, thus, require more energy to move. Their use also requires deeper footings to be drilled in areas with poor soil conditions. The production of steel and concrete is in addition very energy intensive. Steel for instance is created using the Bessemer process, whereby pig iron is melted into liquid form and oxidation impurities are removed to increase its strength. This process requires the matter to reach temperatures of 3600 ºF (2000 ºC). According to Stanford University this process consumes 13.5×10^9 joules of energy per ton of product produced (Martelaro, 2016). In 1995, the IEA estimated mills produced 1.6 to2.2 tons of CO_2 per ton of product produced and accounted for 7% of global carbon emissions (de Beer, et.al. 2003, i). This percentage has increased in the past two decades as nations like China grow their industry and world politicians remain lackadaisical in their response to the climate emergency.

There is hope, however, in a material that does not produce CO_2 when created, but in fact absorbs CO_2 and emits oxygen. It is lightweight, easy to cut and shape, and remarkably strong. This material is not a newcomer either, but rather, it predates the evolution of humans by millions of years. It is mankind's oldest building material of choice with examples of its use dating back to prehistory many thousands of years ago. This material is wood. Wood is one of the only construction materials available that is carbon neutral. A carbon neutral material is a material whose net carbon output from creation to installation is at or near zero. Wood's creation is a carbon negative process, CO_2 is absorbed rather than released. Through the process of photosynthesis CO_2, water, and sunlight are converted into energy for the plant and raw carbon for the assembly of cellulose, the main building block of wood cells. Carbon is released when raw wood is converted into building materials through use of machinery to harvest, sawmill, and transport timber. Yet the carbon release of this process is offset by the wood's initial absorption of carbon. Utilizing locally sourced timber in construction can, by reducing transport need, further reduce carbon output of the process. Wood itself is a lightweight material meaning even with transportation less energy is consumed moving the material. Its lightness is an asset in construction, members are easier and safer to place, and some can even be fitted by hand. This lightness of members translates to lower dead weights the material must overcome. While steel is very strong, a comparison of steel's strength to its own weight finds that a significant portion of the member's load bearing capacity is used to hold its own mass. Wood, in a dead weight to strength ratio, performs better than steel. Finally, the lower weight of individual members leads to a lighter overall system and a lighter weight overall building. A lighter building requires less substantial foundations, an important quality in cities and towns were the load bearing capacity of the soil is poor. Less energy may be consumed in excavation as well.

While wood is not the answer alone to the climate crisis its use in place of steel can significantly reduce the construction industry's carbon footprint. It is important that, as a species, we do everything we can to reduce our carbon output for our survival. Therefore, it is a worthwhile endeavor to use timber in place of steel where possible. While much of our small building stock is indeed wood based the material has not caught on in the large structures sector. It is thus desirable to pursue the implementation of wood in large structures because these buildings have the highest impact on human carbon output in our built environment.

Thankfully, the movement to build with timber is slowly growing. Certainly, wood has dominated the residential sector. Until 20 years ago the proposition that larger structures (which are far more carbon intensive) could be assembled from mass timber was merely a dream. For the past couple decades now, European nations have led the way in large scale timber construction and have made incredible advancements:

> "*In Heilbronn, the tallest timber housing development in Germany was inaugurated – the 34-metre Skaio; and in the next few months, the University of Lucerne will move into a 60-metre-high tower in Risch-Rotkreuz – the tallest timber office block in Switzerland. Both projects will, however, be far exceeded by two timber high-rise structures with mixed uses to be completed this year: the 85.4-metre Mjøstårnet in Brumunddal, Norway, and the 84-metre HoHo in Vienna."* (Kaltenbach, 2019, 29-30).

The 18 story Mjøsa Tower was opened in March of 2019 and currently holds the title for tallest wooden building. It is proof of concept that tall buildings executed in timber are a very real possibility. In the United States, a nation constantly building large structures, mass timber has had a slow start yet there are some prime examples that have helped prove timber's effectiveness. The John W. Olver Design Building, located on the University of Massachusetts at Amherst's campus, is hailed as one the first great Northeastern American examples of mass timber construction. Housing 3 academic departments on 4 floors in 87,000 square feet the structure is in no way small in the class of academic buildings. The building uses a combination of composite cross laminated timber panels, a post and beam arrangement of thick glulams, and state of the art connection details to create a gorgeous model for American mass timber architecture. The building is also quite successful in celebrating its materiality, showing off its wooden nature proudly at every opportunity possible.

It is this celebration of the materiality that makes a large scale timber structure successful. Wood is a beautiful material; warm, welcoming, natural, comforting. Its grain forms dynamic patterns and its texture is friendly to the touch. Studies have shown wood has a positive psychological impact on occupants and still other studies have indicated wood may improve indoor air quality (Health Benefits of Wood, 2020). Wood is also important to celebrate in a structure of its creation by virtue of a concept called "Truth in Materials." Louis Kahn famously asked a brick, "what do you want, brick" and brick replied, "I like an arch." Louis Kahn believed materials had a "stubborn sense of their own identity," that made hiding their true nature inappropriate (Wainwright, 2013). Kahn primarily worked with masonry and concrete however his ideals can apply in our day and age to timber. Honesty in architecture also applies to structural systems. Architectural styles ranging from medieval gothic to the diagrids of Norman Foster find great success in showcasing their structural systems as a piece of art in themselves. Sweeping arches and dancing geometries stimulate the senses whilst contributing to a sense of ease in the occupants' mind. On the other hand, styles that choose to hide their supports seem almost untrustworthy or even dishonest. The White City of Chicago hid steel frames behind layers of staff made to look like white stone, today we may view this as 'tacky,' our perceptions being like finding a beautiful plant in a hotel lobby is made from plastic. The UMass Design Building has been designed with the expression of the wooden structure a top priority and it is this quality that has made the building highly successful with students from all corners of campus. People are consistently fascinated by its crisscrossing wood beams and dramatic scissor truss covered atrium. There is often surprise and wonder following the revelation that this wood is not just a cladding but is the load bearing material. Many of the most modern examples of mass timber structures have expressed their materiality in earnest. Perhaps this is due to the newfound excitement architects have for the material. Perhaps owners enjoy the positive message the material choice sends about themselves. Perhaps the parties involved have a true concern for the environment. No matter the circumstances the current trend for mass timber structures is to express materiality. The question becomes, will this remain the case in the future? Are we using the wood the way it wants to be used? What does a stick want?

When the iron frame was invented, it found itself used expressively on a small scale. The Bibliotheque St Genevieve designed by Henri Labrouste and completed in 1851 was revolutionary in its use of iron framing. Great iron arches supported two massive barrel vaults over a vast open library. The use of this material was new and exciting and yet much of the way it was used reflected a masonry past that designers of the area had yet to depart from. The origin of each massive iron arch was capped by an ionic column, a detail that been intrinsically linked to a classical past hewn from stone (Figure 1). To bring this detail forward in time the capital was crafted from iron. However, this confused the form more; was this a classical building made from iron or an iron building that referenced the past?

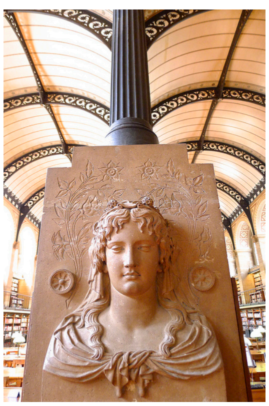

Figure 1: Column base

This sort of trend has continued through the centuries. As new technology comes about it is at first adapted to fit the form of its predecessor. Iron was forced to mimic stone. Is wood mimicking steel and concrete? On an outside glance the use of post and beam glulams with CLT plates in the Design Building seems to recall the bar members of steel construction and the plate characteristics of concrete. From a structural standpoint this system works just fine, loads flow in much the same directions a traditional steel beam and concrete composite deck system might direct them into collector beams sized to support them. CLT plates mimic composite steel decking, transferring forces in two directions yet still maintaining a primary axis. Glulam beams behave as steel I-beams do, converting two-dimensional line loads into one dimensional point loads. Glulam columns act as a column does in any material, transferring loads vertically while resisting buckling and crushing. Yet all these wood analogues to steel and concrete work just well, the building is more than sturdy. Just as the ionic capitals of the Bibliotheque St Genevieve transferred load then and still do over 170 years later. Is there a problem?

The columns of the Design Building are massive. This is a key issue with wood as compared to steel. Member sizes of wood must be significantly larger than their steel counterparts in order to match strength. In the Design Building exists an interesting moment wherein one of the wood columns had to be swapped with a Hollow Steel Section. The size difference is striking, the HSS is a fraction of the average glulam member size. By using an HSS a window in the room finds itself freer to be seen through from all angles of the room. It appears this is a major issue for wood, big members mean less permeable and occupiable space. However, the wood members are not the size they are only due to strength concerns, they are as thick as they are to resist fire, and in fact have an advantage over their steel counterparts.

When wood burns it does so in a very specific and predictable way. The outmost layer of wood exposed the fire combusts and turns into ash. Ash does not burn as well as untouched wood. Therefore, for a fire to continue consuming a wood member it must make it through the ash sheath formed around the member first. The ash has formed a protective layer that has slowed the fire's progress. Wood burns, on average, at a rate of 1.4 inches per hour. Wood that is not exposed to the fire remains undamaged. If an 8" diameter log is burned for one hour before the fire is extinguished one can saw a cross section through the log and find the inner 6.6" of the log unharmed and, more importantly, still structurally sound (Figure 2). Steel on the other hand does not fare so well in a fire. Exposed to heat of 1202 ºF (650°C) a steel beam will become malleable, losing half its strength. Under a force it will bend with ease. It is this principle that makes the art of blacksmithing possible as these temperatures are quite attainable with a normal fire. In a building fire there can be nothing worse than the structural system of a building failing before occupants have had a chance to evacuate. Yet it can take a matter of minutes for a large steel section to deform in a fire. To protect steel, methods such as intumescent paint have been used to protect members from reaching critical temperatures. Steel may also be encased in concrete or like in the design building; it can be encased in wood. So predictable is the rate at which wood burns that it has been accepted into building code as a means to protect steel connections. So, while the girth of the wood

Figure 2- Pre and post fire

columns in the Design Building might be of slight frustration the fire resisting capability of these members can be considered a very reasonable trade off.

As much as there are crossovers between traditional methods and new wood technology modern mass timber structures employ innovative systems that do not have steel analogues and are truly unique to the material. The Design Building's grand atrium features a distinctly timber based tectonic feature, the Zipper Truss. The timber truss uses a series of massive lineal glulam beams that clear span the atrium. A steel tension chord is stretched along the bottom and pushed out by intermediate wood columns that prop themselves between quarter points on the beam and the center of the steel tension rod. This hybrid system resembles a drawn bow and arrow, the beam being the bow, the arrow being the columns, and the bowstring being the tension rod. A bow may flex in the curved shape, but the main glulam of the zipper truss remains flat, rather the forces that would bow the glulam upwards are counteracted by the massive loads of a roof garden above. The system finds itself in equilibrium. This system is unique to long span wood structures and uses both wood and steel where they are most appropriate. It is systems such as these that capture the truth in materiality that we should seek in timber design.

Figure 3- The zipper truss of the UMass Design Building

A hybrid combination of materials is highly effective for more than assemblies like the zipper truss (Figure 3). The Design Building features a complex assortment of connection details the utilize steel where multiaxis forces would not be transferrable by wood. The CLT floors have a layer on concrete a top them to increase their strength but increasing the compression strength on the panel.

The site chosen for this project is one America's fastest growing cities; Denver Colorado. The adventurous and progressive culture of this city makes for an appropriate context to this is exploration of our architectural future. This feeling of adventurism in Denver is in part a due to its location as the gateway to the Front Range, the Rocky Mountains, and the Western United States. These natural locations draw a vibrant outdoor recreation community. The allure of unlimited deep powder skiing, challenging climbing routes, and breathtaking wilderness become one of the largest, if not main reasons millennials flock to Denver increasingly each year. As such it is both proper and almost required that the architecture of Denver reflect this.

With the mass influx of young transplants comes a set of new problems for the city. As with any fast growing city housing stock becomes a bottleneck to growth. Unfortunately, because of a lack of geographical barriers, urban sprawl has been the reaction of Denver's human landscape to this influx. As is well known urban sprawl creates unconnected communities and increases the need for polluting motor vehicles. While this sprawl takes place much of Denver's urban heart remains as parking lots. While Denver is well serviced by rail, bus, and bicycle access these parking lots have yet to be phased out as commuters from the sprawling city outskirts are forced to drive more and more. For this thesis, the building type and location were chosen to ameliorate this problem.

1.3 Literature Review

1.3.1 Literature Review Introduction

This thesis explores the future of large-scale timber structures. Specifically, this thesis addresses the common trend of applying steel and concrete construction methodologies to timber design and proposes possible alternatives that could be better suited both tectonically and aesthetically to wood. The material in this literature review looks at a variety of sources, from the broad topic of timber construction to specific built projects.

1.3.2 A Brief History of Timber

The first source referenced was an excerpt from “Building with Timber: Paths into the Future,” which was published in conjunction with the exhibition “Building with timber - paths into the future,” held at the Architekturmuseum der TU München at the Pinakothek der Moderne, Munich, from 2011 to 2012. It is a collection of articles written by experts from around the world and is concerned with the exploration of wood technology’s future. The work explores how roles have changed between humans and technology in wood construction throughout time, the success of wood structures from the standpoint of tectonics, and the potential parametric design has for the future to realize fully tectonic structures. Wood construction began the age of the *archi tekton* when a master carpenter who not only designed a building but was responsible for its construction and the conversion of forest products into building elements. During this time, builders both responded to and reflected the material’s desires: its natural lengths, strength properties, and aesthetic values. Pieces were cut to fulfill specific needs. With the advent of the Industrial Age, this practice was no longer feasible and as such, wood product geometries became standardized. As the individual *archi tekton* turned into many people representational standards were also developed to facilitate clear communication. The combination of these factors led to generations of buildings whose design responds to the economic needs of industry rather than the nature of the material. Eventually glued timbers were invented, homogenizing the material to increase its strength and efficiency. Panel products also revolutionized the built environment, allowing surfaces to play a role in wood architecture. Panels even reversed the role of bar and panel shaped members, allowing surfaces to transfer loads, using bars for bracing. In the 21st century we have the technology to bring the two best of two pasts together. Our advanced computer technology is now integrated with our fabrication process; thus, the industrial production of purpose-created timber pieces is now a viable option. An assembly line can follow toolpath instructions from software to make a specific piece and move right on the next one; no longer does a carpenter have to spend their time crafting an individual piece nor a manufacturer halt an assembly line to retool. The design of these individual parts is quite complicated, however. The process would involve many hours of designers drafting forms and engineers requiring them to completely redraw those forms. That is until we introduce parametric design to the process.

1.3.3 Aides to Design

A chapter called "Designing Through Experimentation: Timber Joints at the Aalto University Wood Program" was written by Phillip Tidwell and Pekka Heikkinen as part of a book called Rethinking Wood: Future Dimensions of Timber Assembly (2019). This article specifically deals with joint connections with wood but also alludes to one of wood's major benefits, is propensity for disassembly. Wood is lightweight and strong. Unlike concrete, it can be efficient to assemble in smaller pieces. As it becomes more apparent that the end of the building's life, or rather its disassembly and recycling, is a major consideration in a building's carbon footprint, the ability of wood to form structures that can be liquidated and recycled makes it an appealing material to use. However, much of modern timber design is somewhat destructive, using connections that are meant for one time use and render a section of wood unusable when that connection is broken. For example, a screw hole is drilled once, and the threads crush into the wood piece; when the screw is withdrawn the hole cannot be used again and becomes a weak point in the piece's cross section. The research undertaken at Aalto University explored temporary connections that still meet the standard of care. A series of pavilions have demonstrated some exciting possibilities for strong transient timber connections that also benefit the aesthetic qualities of the form. Devising connections that hold these qualities will be a major part of this thesis work and Aalto University's research will serve as a very helpful starting point.

The paper "Hybrid Connections for Timber Structures" is an exploration of connection details that hybridize mechanical and glued connection in wood. Specifically, the paper covers "glued-in rods and plates, and a novel grouting technology with concrete-type adhesives, and hybrid carpentry type joints" (Schober, Tannert, 2016). The paper is dense and is focused on engineering, yet it provides helpful diagrams to intuitively detail connections. Among these diagrams are solutions for space frame structures, a point of interest for this thesis. The paper offers a real-life example of a grouted timber joint used on a composite timber truss bridge. Connections are almost as big of a concern in mass timber design as the wood members themselves and finding safe and efficient details is paramount to successful implementation of mass timber in our built environment.

Another source that was looked at for inspiration was the "Educational Pavilion at Lincoln Park Zoo, Chicago" by Leif Johnson (2012). This article has been taken from *Detail*, a German magazine that analyzes complex detailing in contemporary architecture. In the article the Educational Pavilion at Lincoln Park Zoo in Chicago IL is analyzed from a technological perspective. The pavilion, designed by Studio Gang, is a striking wood structure; consisting of a barrel vault executed in a lattice of curved glulams. The article states, “the constantly curving geometry of the pavilion required the development, testing and fabrication of a new type of glued laminated structural member” (Johnson, 2012, 124), this created some challenges whose solutions can be informative for further research. Because none of the structural members had been used before, they were not safety rated. The APA itself did testing on these new members and the data from these tests were used in design and permitting. For efficiency only two types of structural members were used, making production of the members easier and fabrication on site smoother. During the process of design, it was discovered that creating a denser array of structural bays was far more viably structurally as it spread forces throughout the entire structure. Overall repetitive and dense members were found to be the ideal structural system. Studio Gang’s project suggest that discoveries made during its creation can help in the development of larger structures.

The research paper “River Beech Tower: A Tall Timber Experiment”, presents a study conducted by Perkins and Will, where a theoretical 80 story timber structure was designed for downtown Chicago (2017). Research determined that the ideal way to build wooden skyscrapers is by using a mixture of different wood products including LVL for lineal members arranged in a diagrid, GLT for long span members, NLT for floor plates, and CLT for vertical wall sections. The case study also examined the benefits of a wood structure both environmentally and to the timber industry as a whole. Analysis of the final design concluded that “the timber superstructure performs in a similar way to residential towers of similar heights and size constructed of concrete and steel” (Perkins and Will, 2017). The authors also offered suggestions for how such a structure might be approved by building code officials including methods of encasing wood members, changing legislation, or even genetic modification of wood species to improve fire retardance. This paper can be referred to for design recommendations should the thesis focus on designing a wooden skyscraper.

"The Urban Lung: Timber Skyscraper" featured in *EVolo* magazine is another helpful precedent (2020). This timber skyscraper, designed by architect Ryan Gormley, was designed as a response to a surplus of timber in Wales following a mass felling of trees to prevent the spread of a pathogen. Information comes in the form of an infographic and offers interesting ideas in programing, connection details, and justification for the form of an overall diagrid structure versus a conventional vertical grid. This project will inform some of the design in this thesis.

The paper "Mjøstårnet - Construction of an 81 m Tall Timber Building," featured in Internationales Holzbau-Forum IHF 2017 gives a look at the structure of the world's tallest timber building as of the writing of this thesis (Abrahamsen, 2017). The paper gives an excellent run through of the overall framing system of the tower and provides helpful diagrams. The tower is comprised mainly of timber however its upper floor plates are made of concrete to reduce sway. Overall, the building follows a recognizable post and beam typology without exterior bearing walls. This paper aides this thesis by giving a solid precedent for a functional high rise timber framing system that has already been constructed. The paper also provides valuable information such as member sizing.

1.4 Precedents

The following precedents collected in this thesis are used to inform the design of this project's structural system as well as explore other tectonic features that made them successful. This list of precedents is far from exhaustive but covers a range of design options with major differences being in how architects dealt with lateral forces.

1.4.1 Mjøstårnet- Brumunddal, Norway- Voll Arkitekter AS

Figure 4- Mjøstårnet stands over a lush landscape in Brumunddal, Norway.

Mjøstårnet, or "The Tower of Lake Mjøsa", is an 18-story timber structure and currently stands as the world's tallest wooden structure, standing at 265 ft (81m). Its net area is 121632 sq.ft. (11,300 m^2) and its program includes offices, a hotel, restaurants, apartments, and a roof terrace (Figure 4). The building's structural system is designed as follows.

> "*The main load bearing consists of large-scale glulam trusses along the façades as well as internal columns and beams…. The trusses handle the global forces in*

horizontal and vertical direction and give the building its necessary stiffness. CLT walls are used for secondary load bearing of three elevators and two staircases. The CLT does not contribute to the building's horizontal stability." (Abrahamsen, 2017, 4)

Mjøstårnet primarily uses timber in its super structure and still reaches the impressive height it achieves. The choice for this system considered the flexibility needs of the building's program and thus the building is made from prefabricated parts rather than building modules like the building's contemporaries (Abrahamsen, 2017, 4). The façade of the building is made from prefabricated elements complete with cladding and insulation. This cladding is nonstructural; therefore, the building was able to be topped out before cladding was applied. Structural timber rests inside this outer layer to protect it from rain and sun. The wood also allowed to "breath freely" on the inside (Abrahamsen, 2017, 5-6).

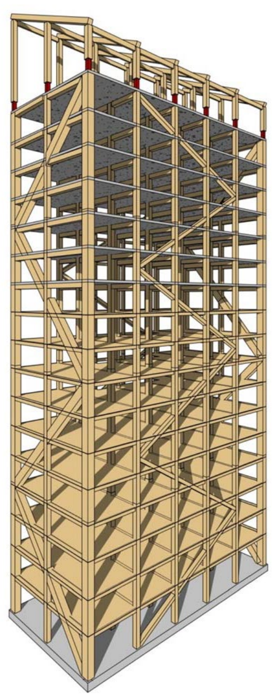

Figure 5- Mjøstårnet structural system 3D diagram

A very interesting feature of this structure is that, despite being mostly timber, floors 12-18 of the structure are executed in concrete. By making the building top heavy it was able to fit the comfort criteria for sway in the structure. Otherwise, because the building is slender in its weak direction, occupants may suffer from motion sickness as wind moves the tower. Abrahamsen points out this feature improved acoustical performance in the building as well. For actual member dimensions, glulam beams supporting timber floors are 15.5 x 23 in (395x585 mm) and

15.5 x 26.5 in (395x675 mm). Typical glulam beams supporting concrete floors are 24.6 x 23 in (625x585 mm) and 24.6 x 28.3 in (625x720 mm). The largest diagonal cross section is 24.6 x 38.9 in (625x990 mm) (Abrahamsen, 2017). No doubt these are large members, however they are still reasonably accommodating for interior spaces as can be seen in Figure 5 and 8. Elevator shafts are made from CLT and stretch 74m through the building. The topmost floor features and an apartment and a pergola. The pergola is a separate structure bolted onto the 18th floor's concrete deck. Structural connections are made using slotted steel plates fixed by dowels. The floor plates are a combination of glulam and LVL, insulated with Rockwool ® and finished with a 50mm concrete screed on top.

Fire protection is a critical issue in mass timber design. However, the design and testing that went into Mjøstårnet shows that heavy timber's response can be both elegant and effective. Code dictated, "main load bearing system must be designed to withstand 120 minutes of fire. Secondary load bearing such as floors must withstand 90 minutes of fire. (Abrahamsen, 6)." Burn testing was performed at SP Firetech in Trondhiem, Norway. The results of this study proved promising to the project and to all mass timber projects. Glulam members passed their tests, after the burners were shut off the wood was allowed to char. This continued burned eventually died out after a couple hours. Thus, showing that large glulam column eventually self-extinguish and continue to support loading. Numerous other fire considerations were implemented. Visible wood in escape routes, main staircase, and elevators was given fire retardant

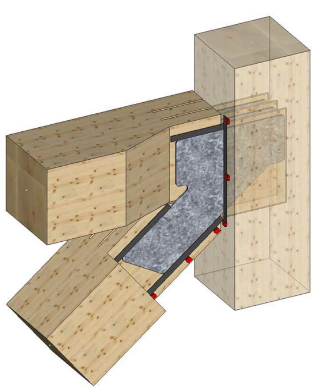

Figure 6- Fire resistant detailing in Mjøstårnet

paint. The whole building is sprinkled. The façade includes Firestop to prevent fire from moving upwards. Steel connection plates are packed into the wood members to shield them from fire exposure. The slots that are left exposed are fitted with an intumescent fire strip that expands when heated above 150 degrees Celsius (Figure 6). Dowels where not plugged as testing showed doing so does not affect the internal steel's temperature. For redundancy, the structure is designed to maintain strength in the event a floor is lost. The structure can also survive one floor falling onto the floor below.

Floor plates in this tower more closely resemble a conventional wood floor system with horizontal line members as opposed to CLT plates. The system was based off another project's system, the Metsä Wood RIPA deck system, also referred to as the Trä8 building system (Figure 7). The system is assembled from glulam and LVL beams.

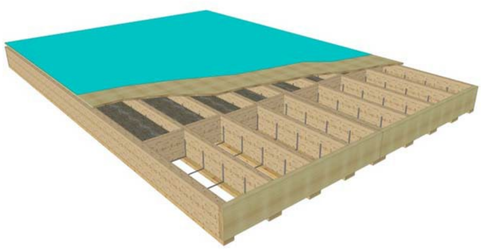

Figure 7- Assembled floor system

In the US, this system would be easier material wise to procure than CLT. Abrahasen also points out this system uses less material than CLT and is light and quick to assemble. He goes on to say, "The floors become very stiff and perform well. They can handle both acoustic requirements and fire requirements. The carbon footprint is particularly low, estimated at about 13.31 lbs CO2/sq.ft. (65 kg CO2/m2). Floor spans of almost 32 ft (10 m) is within reach with this technology. This increases flexibility compared to other timber-based floors" (Abrahamsen, 2017).

The program of Mjøstårnet is rather diverse. On the lowest 2 floors are a restaurant and conference spaces, 5 levels above are offices, 4 above this is a hotel, and the remaining 6 floors are apartments. The difference in programing is articulated on the façade with different window patterning, the apartments feature cantilever sections.

Of note is Mjøstårnet's outer appearance. The façade celebrates the materiality of the building by giving it a warm wooden finish. The glulam pergola on the roof is also left exposed to further celebrate the wooden superstructure of Mjøstårnet. Architectural expression of a building's nature adds to its tectonic effectiveness and Mjøstårnet does so beautifully.

Mjøstårnet is a real-life example of the structure proposed by this thesis. We know that tall timber structures like this are very possible and the existence of this project stands as proof. However, the point of this thesis is not to ask if it is possible but rather to explore design options for timber towers. So, what can we learn from Mjøstårnet? First and foremost, we learn that a hybrid Timber/Concrete is not only appropriate for a tall timber structure but in this case was a necessity for occupant comfort. While full wind analysis is outside the scope of this thesis it is still an important consideration, Mjøstårnet is an example of a timber tower's response. Second, we learn important fire detailing from Mjøstårnet. Much research and testing went into the design of Mjøstårnet's connections. Its connections are proven, accepted by European code, and even familiar in the UMass design building. It is prudent to use them in this thesis design. The program of Mjøstårnet, while including apartments, is still quite different from this thesis. That said Mjøstårnet's system has been designed to allow for maximum interior flexibility, which is important to any program. Finally, the replacement of CLT with stick-frame-like floor panels is an interesting method of reducing timber consumption and making construction easier. Laminated Veneer Lumber and Glulams are also far more widely available in the

United States and especially in Denver given its proximity to major LVL manufactures in Idaho. Therefore, from an efficiency standpoint using LVL and Glulam over CLT is a good idea for this thesis.

Figure 8- Mjøstårnet residential floor plan

1.4.2 Brock Commons- Vancouver, BC- Acton Ostry Architects Inc.

Figure 9- Brock Commons in the city skyline

“To facilitate the use of wood in the high-rise, a deliberate decision was made to limit the areas of innovation to the structural system” (Canadian Wood Council, 12).

Figure 10- Lateral concrete cores were visible during construction

Brock commons is a 177 ft (54 m) tall student resident tower on the University of British Columbia’s campus in Vancouver, BC (Figure 9). Brock Common’s uses a ‘keep it simple’ approach, opting for the most straightforward solutions to avoid issues with restrictive building code. As it stands currently building code has few provisions for tall wood structures and requires comprehensive scientific studies in their approval process. Until code catches up tall wood buildings will have to be approved on a case by case basis. Therefore, Brock Commons combined the innovation of Mass Timber with conventional means of construction such as concrete cores (Figure 10) and fireproof gypsum.

Programmatically the building houses 404 students in studio and four bedroom units. The building also includes public amenity spaces, assembly and study rooms on the ground floor, and a study social space on the 18^{th} (top) floor. The lounge is the only section where glulam beams are left visible.

The lowest floor of Brock Commons (visible in Figure 10) is executed in concrete with an independent structural grid. The ceiling of this level is a thick concrete transfer slab which supports the tighter wood-based grid above. Using this system, the bottom floor can use a wider column spacing accommodating of assembly spaces. The next 16 levels are comprised of CLT slabs supported on GLT or PSL columns and connected by steel. The CLT slabs are two way spanning, similar to a two way concrete slab, and thus require no beams. The lack of beams significantly decreases floor depth. Lateral loading is carried through the CLT floor plates to full height concrete shafts. The connection is made through steel drag strips and ledge angles, "The CLT panels and connections for the structure had to be designed to remain elastic for energy dissipation when the cores yield in flexure" (Canadian Wood Council, 19). Floor plate diaphragm are connected via plywood splines. Because timber structures are lighter than concrete and advantage and a disadvantage are created; Due to a lighter overall building weight, foundations may be smaller and built on a wider variety of soils. Unfortunately, a timber high rise is more susceptible to wind and seismic forces. Brock Commons therefore relies on its concrete cores to resist overturning forces. An assumption too was made that the added weight of interior partitions, systems, and programming would increase building weight enough to reduce sway.

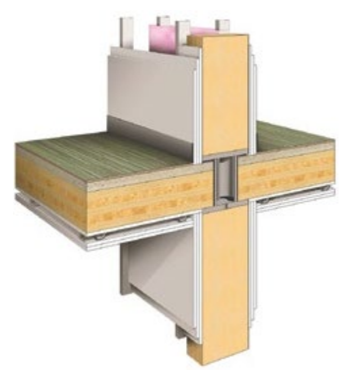

Figure 11- Fire proof detail in Brock Commons

For fire protection the wooden elements in Brock Commons are encased in 3 layers of Type X gypsum wallboard, giving a 3-hour rated barrier (Figure 11). The advantages of this are twofold; First the system is an 'easier sell' to code officials by using a tried and true method of protection. The second advantage is a decrease in member sizing. For a timber structure with exposed members to function the cross section of members have to be wider with the outer inches being considered sacrificial and able to burn away while the interior section remains untouched and stays thick enough to carry loading. By covering timber members in GWB the sacrificial layer of wood is no longer needed, and a member only as wide as is needed for structural support may be used.

Wood, as a load bearing material, is affected by load duration. Wood is far stronger in impact loading than in long term. Wood columns tend to shrink in compression and wood beams have a tendency to creep over time. A tall timber building is not exempt from these realities. The Canadian Wood Council makes the assertion, however, that "When properly addressed during the design phase, however, axial shortening and shrinkage should not negatively impact construction or long-term performance of a tall wood building" (CWC, 20). To combat axial shortening of columns steel shim plates were added to column-column connections, HVAC and mechanical systems were designed to accept 1.25 in (32mm) of deflection, and permanent sensors were installed to monitored by UBC.

Figure 12- Prefabricated façade elements being placed

Construction was a very efficient process of off-site factory produced elements that were assembled on site. Similar to Mjøstårnet the façade is also made of insulated prefabricated elements (Figure 12). This method of construction saves much time on site. Production of elements in a factory setting limits defects. Assembly onsite is faster and requires only a small crew to hoist and place elements. Items fit snugly and reduce air and moisture leakage opportunities. According to CWC the cladding of the façade panels is a "70% wood fiber" composite (29). Windows were also installed before delivery to the site. Further opportunities for efficiency were found in the fact a crane could place the façade panels on a newly finished level before beginning to place the next level.

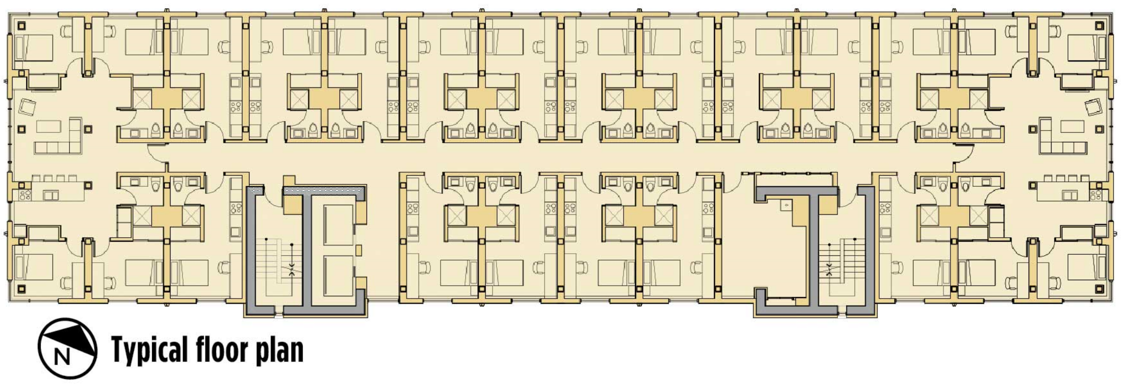

Figure 13- Typical floor plan for Brock Commons

1.4.3 Origine- Quebec City, QC- Yvan Blouin Archtecte

Figure 14- Origine Tower in Quebec City

Origine is the world's tallest fully wooden structure (Figure 14). Standing at 134ft (40.9 m) the tower boasts an impressive 12 fully wooden stories atop a concrete podium. Unlike other tall wood structures there are no concrete cores, or concrete upper stories, just CLT and Glulam plates and beams. The structure is a collection of luxury apartments that abut a river and are treated to sweeping views of Quebec City.

> *"The spot was coveted by many who wanted to create a dynamic living environment. The Quebec City council saw the opportunity to create a new neighborhood that would showcase sustainable development. The land developers selected by the city were tasked with developing the area sustainably and offering eco-responsible solutions. Therefore, using wood in the structures was natural"* (Cecobois, 2018, 1).

The building sports 92 luxury units of studio and 1-3 bedroom arrangements. Units each have a private terrace. The building's commitment to sustainability goes beyond its wooden frame. A bike path cuts through the adjacent park and connects the site to the entire St. Charles River. Heating is provided through radiant floor pipes, A/C was not added due to the cold climate, but the design allows for its addition later. A double vertical chute separates garbage from recyclables. Further, Kitchen sinks have a garbage disposal unit that shreds table scraps and sucks them into a tank in the basement, where, after decanting, the liquid part is sent to a water treatment plant and solids are converted into compost using biomethanization" (Cecobois, 2018, 3). The roof membrane is a reflective white to reduce the heat island effect. Finally, the solid CLT exterior walls act as a superior air barrier and the lack of steel studs reduce heat bridging.

Wood, in addition to its already mentioned sustainable benefits, greatly suited the site of the project. The soil conditions of the riverbank were poor. Therefore, because wood construction is lightweight a taller structure was possible. Origine is built on a 3 ft (1 m) thick floating concrete slab that was poured directly at water table without the need for expensive piles. So light is wood construction in fact, "the building weighs the same amount as the volume of earth that was excavated for construction, so the local load borne by the floating concrete foundation did not change" (Cecobois, 2018, 4). Cecobois further states the same building executed in concrete would have been limited to 6 stories, therefore decreasing the amount of units able to be fit on the parcel of land, reducing profitability, and thus raising the cost of individual units (2018). Another advantage of the choice of wood was a speedy construction process. Because subcontractors do not have to wait for concrete to cure work could begin on finishing lower levels as upper levels were still being placed. Origine went up in 4 months, architect Yvan Blouin believes a similar sized concrete project would've taken 8-10 months (Cecobois, 2018, 5).

Origine was a sister project to Brock Commons in that partial funding was provided by the Canadian government as an investment in the country's sustainable future. The key difference between the two however is while Brock Commons strove for simplicity and efficiency, Origine pushes the limits of what is possible in mass timber construction. The most dramatic element of Origine is a fully wooden lateral resistance system.

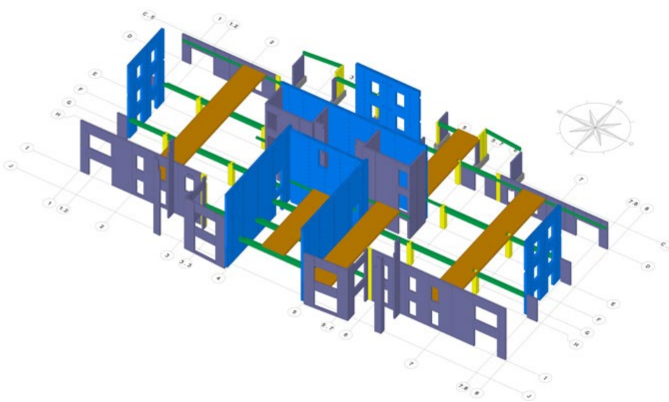

Figure 15- Structural unit of Origine

As shown in Figure 15 the entire building is a composition of CLT and beam elements that together provide rigidity. There are several large CLT shear walls (shown in blue) to begin. These start as 9 ply thick panels and as the building rises are reduced to 7-5 layer panels are loads are lower. Floors (shown in brown) act as diaphragms and push loads to the shear walls. Gravity loading is taken care of by the exterior walls (shown in purple), these are consistently 5 ply panels to meet 2-hour fire resistance. Post and beam construction (shown in green and yellow) transfers floor loading to these walls as well as the shear walls. Shear walls and posts run vertically continuous through the building like a balloon frame system. This is to reduce moments of stresses perpendicular to wood grain and therefore improves overall strength and mitigates vertical movement. To connect floors and beams to these tall members 'ledger plates' and beam pockets are used respectively. As examples of these connections are circled in Figure 16. The connections are finished with large diagonal screws. By essentially separating vertical and horizontal systems vertical members can transfer gravity loads without affecting horizontal members. Other clever details include steel shear keys which turn the connection of two adjacent vertical CLT panels from a 400 nail plate to small efficient keys.

For fire safety Origine was required to have 2 hours of fire protection. Mass timber design gains fire safety typically by recognizing that wood chars at a predictable rate and compensates by providing additional material that is 'sacrificial' in nature. In this way a structure can be given a 2 hour rating if the properly sized cross section of wood remains after 2 hours of wood is burnt away. However, providing an extra 3" of cross section around each and every wood member in a building is expensive and not very space efficient. So, to reach a 2 hour safety rating the designers of Origine provided 1 hour's worth of extra material and then a layer of Type X Gypsum wall board. Extensive fire testing showed the gypsum prevented the CLT from igniting and contributing to a fire. A full size mockup was subjected to a worst case scenario burn and it was found the assembly performed just as well as any conventional building. For added fire safety any non-load bearing partition wall used light frame steel and each unit was designed to be separate from each other and contain a blaze.

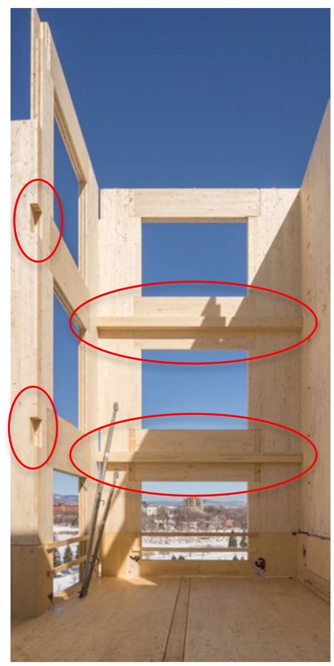

Figure 16- Ledgers and pockets for horizontal bearing

1.4.4 River Beech Tower- Chicago IL- Perkins and Will (theoretical project)

Figure 17- River Beech Tower by Perkins and Will

While the River Beech Tower does not exist in the physical realm, its presence in Mass Timber discourse weighs heavy (Figure 17). Perkins and Will, a firm that performs much research and development on top of professional practice, collaborated with engineering firm Thornton Tomasetti and the University of Cambridge's Centre for Natural Material Innovation to design an 80 story tower supported entirely from wood. The 800 ft (244 m) tall, 300 unit residential tower would sit alongside the South Branch of the Chicago River. Architecturally the designers felt "exposed mass timber would offer a unique experience within the residential market by connecting occupants with natural materials" (Sanner, 2017, 40). Design hierarchy placed importance on establishing a fully timber superstructure and allowing architecture and planning to respond. The team came up with a series of design strategies that can be used almost as a template for similar projects.

Strategy One: “Proportion the tower footprint to make a timber structure more feasible.” As a rule, a wider tower footprint increases lateral stability, this is a fairly intuitive concept. Of course, as many architects know residential floor planning prefers thinner building profiles to maximize perimeter and minimize windowless interior. Therefore, the River Beech Tower is in fact two towers tied together by massive glulam elements across a vast atrium. This can be seen in the overall building form (Figure 17) and more closely in Figure 18.

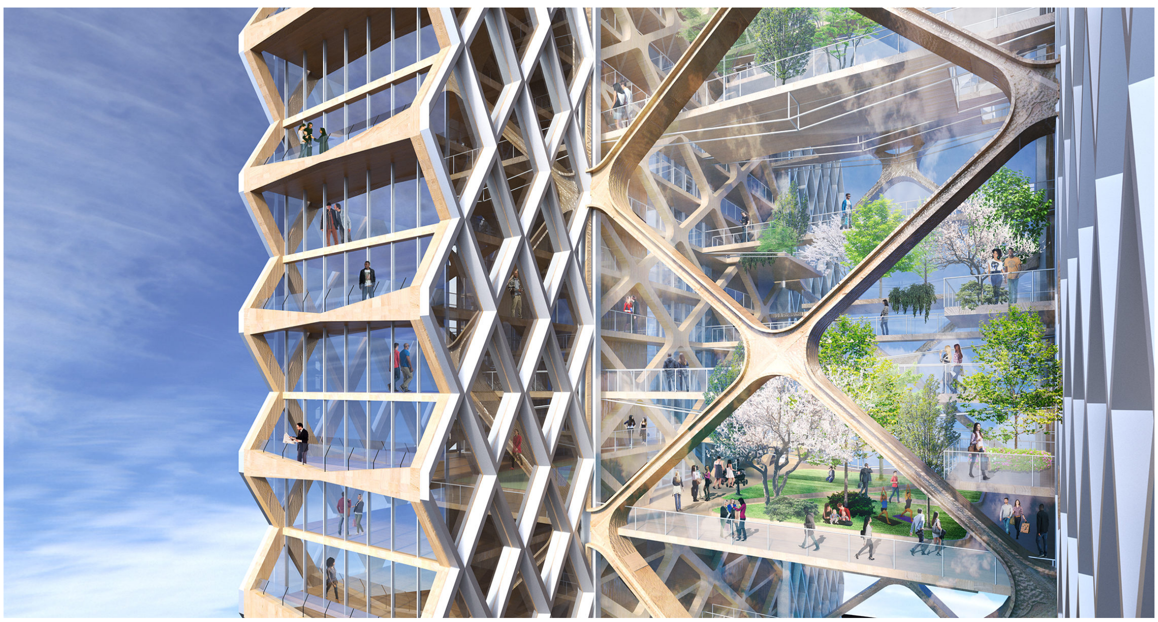

Figure 18- Rendering of the River Beech Tower

Strategy Two: “Maximize the participation of all vertical members of the tower's lateral system.” Wood is strongest in forces parallel to its grain; therefore, structural systems should be designed to channel forces lengthwise down members. Origine did so with balloon framing, transferring forces vertically through panels and avoiding crushing forces. River Beech does so with a very dramatic and exciting diagrid system. Diagrid systems are very effective at converting multidirectional forces into forces parallel to wood grain. Figure 19 illustrates how diagrids reduce bending and moment stresses in members where a conventional square frame would not.

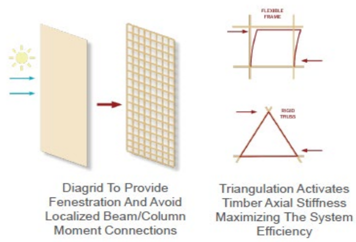

Figure 19- Façade study

Strategy Three: "Arrange the timber material in plan for maximum effectiveness." Forces are transferred equally among members in plan. By balancing forces, the designers guarantee that as the wood naturally shrinks it does so equally across the entire level.

Strategy Four: "Use the material in its most naturally effective way." This strategy connects back to the overall theme of this thesis; what does wood as material want? River Beech answers it very effectively; use each wood product to hold the type of loading it is best at holding. Axial loading is handled by linear engineered wood products, LVL, PSL, GLT, and Glulams. Glulams are best suited for large load, long, unbraced connections; therefore, glulams comprise the massive cross bracing that connects the two towers of River Beech together. PSL and GLT are apt at controlling small localized compressive loading; these products make up vertical columns. LVL is well suited for axial loading, some bending support, and applications that require large material quantities while maintaining an economic advantage; LVL is used for the numerous diagrid members as it is a stock yet strong material. For area loading and shear Mass Timber offers two main products: CLT and NLT. Nail Laminated Timber is timber's answer to the one way steel or concrete panel and is an effective decking material when load only needs to move in one direction; NLT is used in floor plates and spans one direction from the diagrid perimeter to shear walls. CLT, as seen on previous projects, is an effective two way panel product providing strength in multiple directions; CLT is used for lateral force resisting core walls wherein forces are numerous and varied. Figure 20 is a fantastic illustration of how River Beech matches material to location.

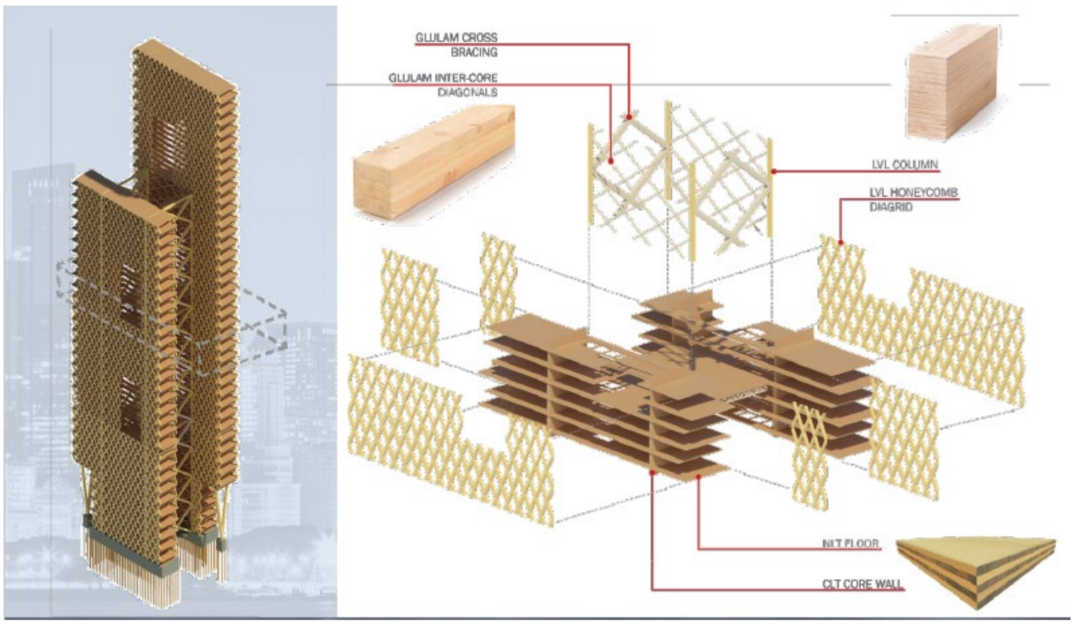

Figure 20- Structrual diagram of The River Beech Tower

Strategy Five: “Expect to use more material with timber than if using steel or concrete.” There is no question that wood, while very powerful, is still weaker than concrete and steel relative to its volume. Therefore, to achieve similar building proportions to conventional buildings a higher portion of the Mass Timber building’s volume will be wood. Systems like LVL diagrids push this extra volume to the outside of the building to create more open spaces on the interior. In general designers should plan program to not be derailed by increased material volumes.

Strategy Six is worded specifically to Chicago but in general applies to all mass timber. Mass Timber is fantastic for modular applications and offsite manufacturing is the key to this. The River Beech Tower would have entire units built on the shore of Lake

Michigan and brought to the site via a barge. The idea of using the Chicago River as a means of transport itself is very interesting. If materials can be brought in this way the project would save immensely by not having to truck in materials through the dense city. Unfortunately, the site in Denver, while located along Cherry Creek, cannot be reached by barge because of manmade obstructions in the water. In general, though, limited on-site construction leads to fewer errors, shorter build times, fewer weather delays, and overall a lower cost of construction.

CHAPTER 2

THE SITE

2.1 Intro

Figure 21- Project Site and context. 1388 Larimer St, Denver, CO 80202

The site chosen is currently a parking lot located between an expansive river walkway and a significant cultural area of the downtown (Figure 21). The building will be designed for a new young generation of Denver residents who live for the weekends in the mountains. The architecture will feature amenities geared towards members of the outdoor community including a gym that features climbing walls and storage for recreational equipment. The site's location is situated well for views of the Front Range, skiers need only look out their window to see snow conditions. The parking lot across the river will be annexed by the project to allow residents to keep a car, a necessity for outdoor exploration. However, the hope is those cars will only be needed on the weekend as a resident's daily commute will be simply crossing the street into the adjacent downtown or to the University of Colorado, Denver campus.

2.2 The Neighborhood- LoDo

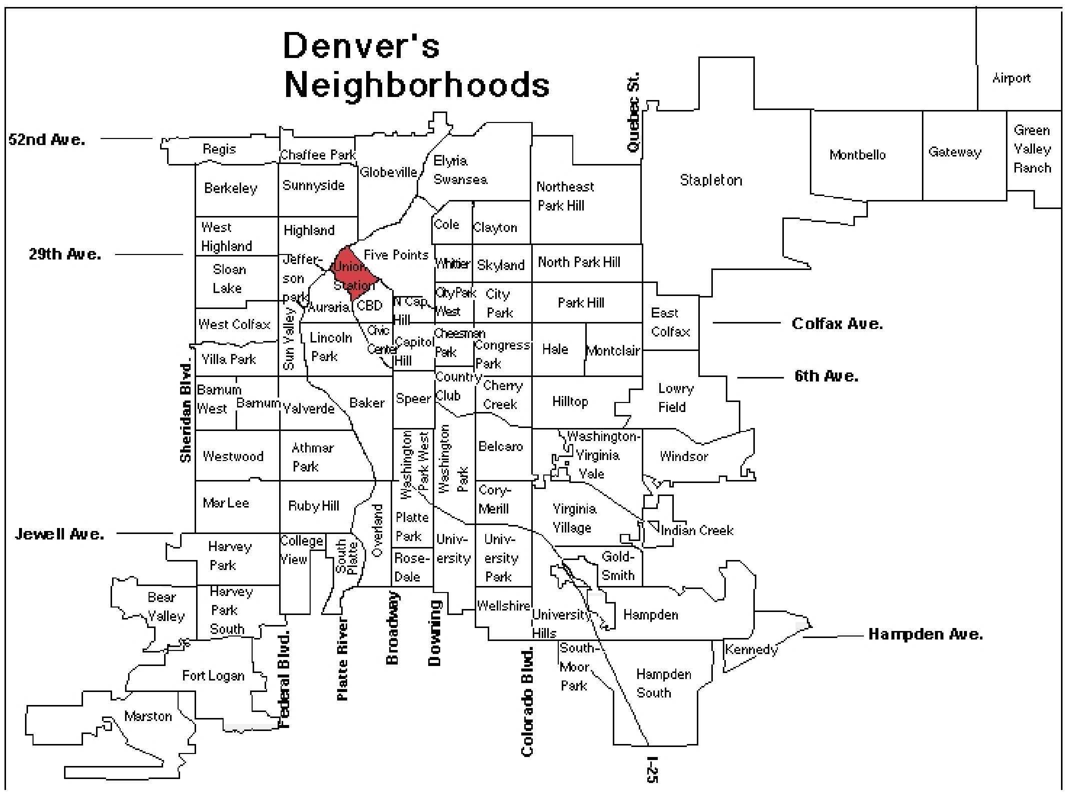

Figure 22- Location of LoDo in Denver CO

Historically the LoDo neighborhood (LoDo being short for Lower Downtown) was settled by the Arapaho Tribe, with encanments along the South Platte River (Figure 22). In 1858, after European settlers discovered gold in the river, colonization of the area increased. As the story goes General William Larimer founded Denver by laying out cottonwood logs in the middle of a square mile plot in the site that is now the LoDo neighborhood. Therefore, making LoDo the original and oldest neighborhood of Denver.

LoDo has always been an active area, sometimes holding the vices of the city. Sadly, in 1864 it hosted a celebration of the white man’s atrocities against the native population when the severed heads of Arapaho people were paraded around the city. In the 1870’s the railroad was finally brought into Denver as a spur from Cheyenne Wyoming. Union Station became the major entry to Denver and LoDo was the first neighborhood one would see upon arrival. Later in the decade and onto the 1880’s LoDo became Denver’s Chinatown, sadly this was torn down in race riots. In the mid-twentieth century the area became impoverished and fell into disrepair. This was due in large part to the diminishing role of the passenger railroad in favor of road and air travel. In 1988 the city officially zoned the area as the “LoDo” neighborhood and set forth a plan for the area’s revitalization. The area was established as a historic district, its old buildings preserved, and new construction regulated. Mixed use development was encouraged and soon the area grew to become a magnet destination. Coors Field and the Pepsi Center brought professional sports to the area, culture and nightlife blossomed (“LoDo, Denver”). LoDo now stands as a success story for urban renewal and second chances. As seen in Figure 23 the neighborhood is charming and vibrant. Even during the COVID19 crisis.

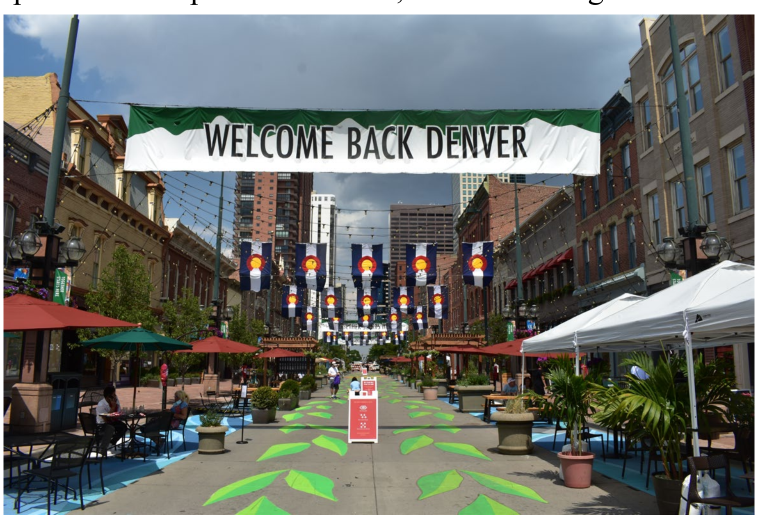

Figure 23- LoDo neighborhood, Summer 2020

2.3 The Site

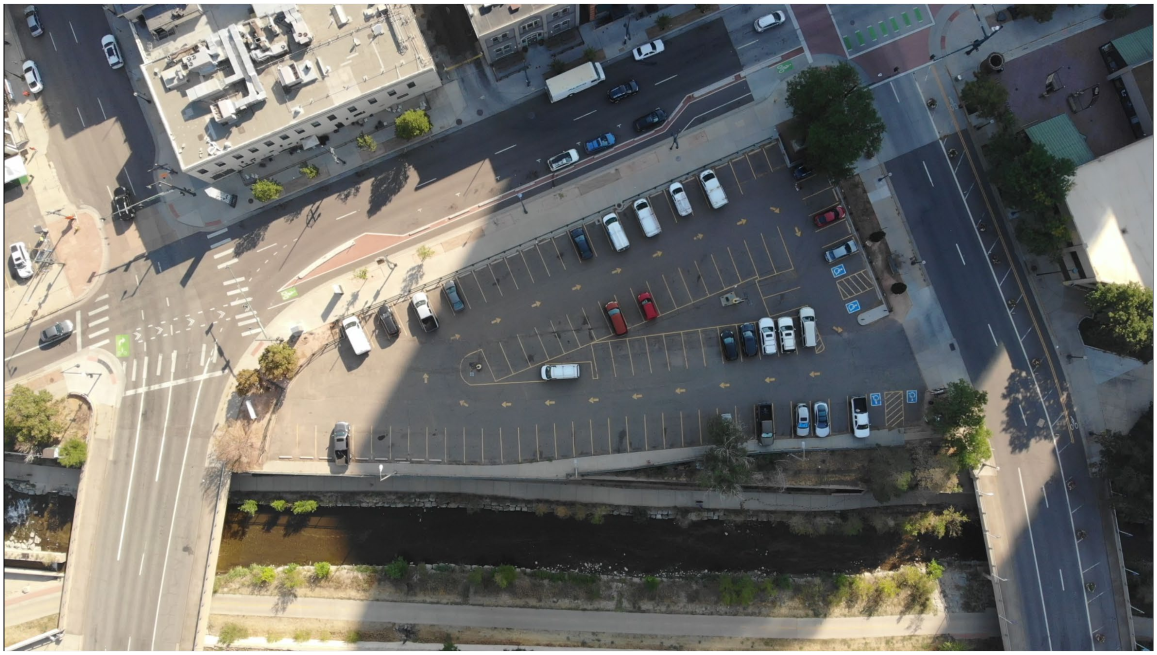

Figure 24- Drone shot of the project site

Currently the home of a parking lot the project site at 1388 Larimer Street is bounded on 3 sides by one way streets and Cherry Creek. In the upper right of Figure 24 is a major pedestrian intersection that connects the scene in Figure 23 to the Cherry Creek trail, an inlet of which is in the bottom right of Figure 24. The Cherry Creek Trail is a bike/ pedestrian path that runs all the way north to Confluence park and as far south as Cherry Creek State Park. The Cherry Creek Trail connects to a network of bike trails that run across the city and provide a sustainable option for commuters. Across the bridges from the site is another lot, owned by the same parking company. This site will serve as the parking lot for the proposed building. The roads across the bridge from the site is a major artery around the city. It connects the site to major highways. This is ideal for both construction and for tenants to be able to adventure on the weekends. Further west of the site is the University of Colorado's Denver Campus, Elitch Gardens (a theme park), and the Pepsi Center (home of the Colorado Avalanche and Denver Nuggets). The immediate north of the site doesn't have the same level of development as the other axis. However. there is a good mix of housing and historic structures. It is likely this area will see further growth in the future and should be treated as such. Figures 25-31 are photos of the site context.

Figure 25- View of site from North West across the creek

Figure 26- View of site from South West across the creek

Figure 27- View further north along Cherry Creek Trail showing area's mixture of historic and contemporary architecture.

Figure 28- View 400' above site looking North. Note haze from wildfire smoke obscures horizon.

Figure 29- View 400' above site looking West into city.

Figure 30- View 400' above site looking South. Note haze from wildfire smoke obscures views of the Rocky Mountains that would typically be visible on the horizon.

Figure 31- View looking West across street from site. Parking meters of current site visible to right. Entry to Cherry Creek Trail is on the right before the bridge. Rocky Mountains visible on horizon before smoke covered them during drone flight.

2.4 Local Climate Considerations

Denver is located in Climate Zone 5B according to ASHRAE (Denver County, Colorado ASHRAE 169-2006 Climate Zone | Open Energy Information, 2021). Denver is semiarid with low humidity, plentiful sunshine, and occasional very cold temperatures. Denver is considered a milder climate than the neighboring Rocky Mountains and Great Plains. Denver earns the nickname "The Mile High City" from the fact that the city sits around 5,280 feet above sea level. Visitors to the city who are used to oxygen rich sea level air can often feel lightheaded and easily winded from the thinner atmosphere. Denver's weather stays relatively stable due to shielding by the Rocky Mountains though early and late season snowfall are a common occurrence. Throughout all seasons, with occasional spikes, the shielding of the mountains keeps the humidity levels of the city low (Geography of Denver, 2021).

As a city Denver has set an ambitious goal called the 80x50 Climate Action Plan. This goal is "an 80% reduction in greenhouse gas (GHG) emissions by 2050" (The Office of Climate Action, Sustainability, and Resiliency, and New Buildings Institute, 2021). Reducing building environmental impact is a huge part of the plan. Table 1 shows a timeline for building construction energy goals from now until 2050.

Table 1- Denver's climate action goals (The Office of Climate Action, Sustainability, and Resiliency, and New Buildings Institute, 2021)

Year	Buildings Goal	Homes Goal
2025		• Homes use 10% less energy
2030	• Buildings use 30% less energy	
2035	• Net zero energy new buildings	• Homes use 20% less energy
2040	• Buildings reduce heating emissions 50%	• Homes reduce heating emissions 25%

Source: CASR

For this thesis, the interest of sustainability is a major component, if not the reason for us to explore mass timber technology. Therefore, in addition to the use of timber energy saving strategies will also be implemented, especially passive systems. It is appropriate and almost required to do so. Energy modelling is not being conducted for this project, however. While not unlikely this building would meet Denver’s 80x50 goal, this thesis will not be able to say for a fact that it meets the goal.

CHAPTER 3

PROGRAMING AND PLANNING

3.1 Introduction

Denver as a growing city is in need of housing. Currently the city is growing outwards quickly. This is leading to the problematic phenomenon of Urban Sprawl. As the city grows so too do housing prices as existing housing stock cannot keep up with demand. Gentrification occurs on the outskirts of the city as housing in downtown fills up and higher income individuals to move outwards. Building a residential tower in LoDo will not single handedly solve these issues, however it will be a step in the right direction. It will house people closer to work and play, consolidating population and reducing daily automotive travel. Given its location it is likely occupants of this structure will be higher income; therefore, this tower will help to avoid displacing others in increasingly gentrified neighborhoods. Architecturally expressing the tower's wooden nature in such a highly visible spot will also serve to promote similar sustainable structures in the future. High income tenants are potentially decision makers for larger organizations. Connecting them to nature through materiality hopefully will influence these tenants to make environmentally conscience decisions in their roles.

3.2 Programming and Site Planning

The tower will be mixed use and acts as a filter between LoDo's most vibrant street and the Cherry Creek Trail. Its footprint will take up the entire site as parking will be provided across the street. The ground floor will be commercial space that faces the

Southern aspect of the site. This commercial space will wrap around both the East and West faces of the building. The Western commercial space will overlook Cherry Creek. The North Western and Northern edges of the building will house a large, glazed lobby. The North Eastern edge will have a small inlet for service vehicles as the intersection on the North of the site is tight and the real estate on other faces is too valuable.

The commercial spaces on the first floor will be a café restaurant and a large retail space. The main lobby will serve as resident entry and as the entry for the second floor climbing gym. The gym takes up most of the second floor and features tall climbing walls for top rope and lead as well as bouldering walls on the periphery and a section for traditional fitness. The north end of the second floor will be work from home offices and be found on the second and third story.

Upper floors will be residential units that run along the perimeter of the structure. They will be mostly single bedroom units ranging from 460 ft^2 micro units to 830 ft^2 units. On the corners of the building will be two bedroom and three bedroom units.

Upper floors will have accessible roof space to be used as communal gardening and gathering spaces. Each floor will have two of these spaces as well as two greenhouses. The highest point of the building will have a rooftop pool that is open air in summer and enclosed in winter.

Table 2 shows a breakdown of the programming of the building. Listed are program types sorted by public/private. Also shown are number of instances and square footages. Circulation space is not shown in this table.

Table 2: Building programming and square footages

Table 2: Building Programming		
Space type	Instances	Square footage
Public Spaces		
Lobby	1	7817 s.f.
Retail	1	9710 s.f.
Dining/Cafe	1	6135 s.f
Climbing Gym	1	22576 s.f.
Residents Only		
Service Bay	1	1388 s.f.
Basement	1	31975 s.f.
Stair Sets	4	N/A
Elevators	5	N/A
Resident Lounges	5	808 s.f. – 1131 s.f.
Work From Home Spaces	36	110 s.f. – 238 s.f.
Greenhouses	16	375 s.f. – 401 s.f.
Outdoor Garden	19	1115 s.f. – 1224 s.f.
Rooftop Pool	1	3555 s.f.
Private		
One Bedroom	193	460 s.f. – 860 s.f.
Two Bedroom	21	641 s.f. – 1293 s.f.
Three Bedroom	15	1191 s.f. – 1510 s.f.

CHAPTER 4

TECTONIC DESIGN

4.1 Introduction

The following chapter describes the design of the tower from a structural and architectural perspective. After a brief review of elements gleaned from the precedent study some basic theory behind timber design is discussed. This theory is then applied to a structural system that is repeated throughout the building. The system is implemented, and the architectural design of the resulting building is discussed from the ground up. In addition, there is a section on non-wood sustainable strategies.

4.2 Design Elements from Precedents

Each precedent contributed to this project in some way, however the most influential project was the River Beech Tower. The family resemblance is clear looking at the façade of this project and that of the River Beech Tower. What the River Beech Tower inspired was the strategic use of different engineered wood products where they were best suited. This is the most effective design strategy this thesis has found for mass timber design. Many contemporary projects follow a practice of “CLT-washing” wherein CLT is considered the solution to all design problems. While, yes, CLT is a highly versatile material that does not necessarily make it the best solution in all applications.

4.3 A Brief Lesson on Timber

As mentioned earlier wood is an isotropic material. As such it responds differently to forces depending on the orientation of those forces to the grain direction of the wood, demonstrated in Figure 32. This is because wood is a collection of long cells held together by a material called lignin. Lignin is strong but not as strong as the cells themselves, therefore is element of the wood that fails in loading.

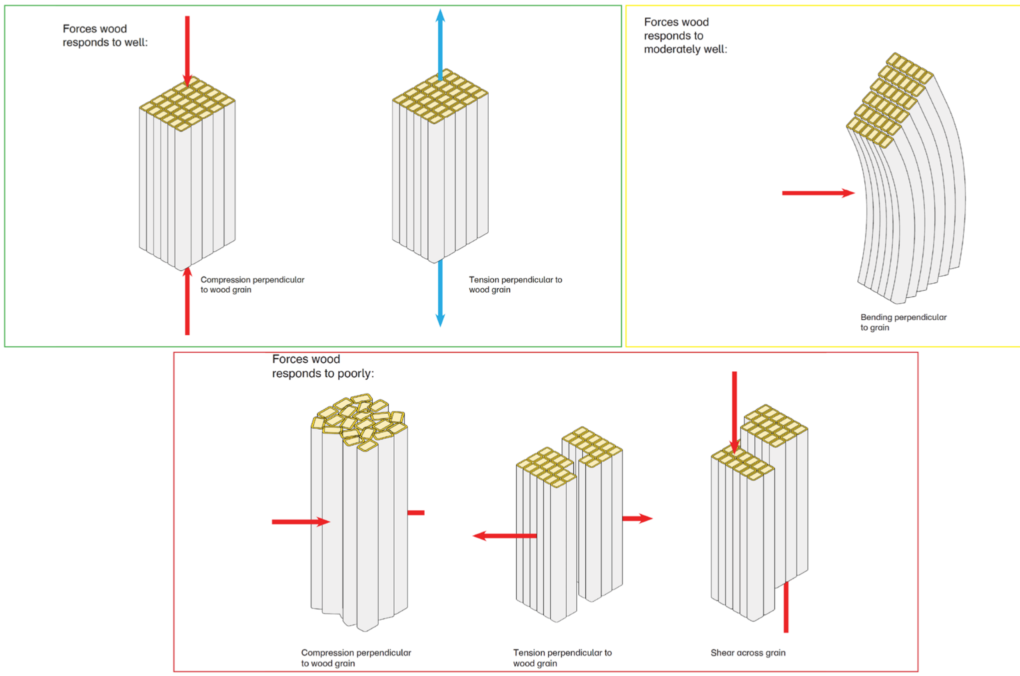

Figure 32- Wood cellular structure and how it responds to loading.

The US Department of Agriculture Forest Service provides tabulated values for the strength properties of many commercially important species of wood. Shown in Table 3 is an excerpt from one of these tables showing a couple commercially available softwood species. The values printed show a specie's mechanical properties such as its bending strength, compression strength both parallel and perpendicular to grain, shear, and tension perpendicular to grain. Tensile strength parallel to grain is not printed in this table. Note the values for compression parallel and perpendicular to grain and compare the two values for any given species. Let us take Interior West Douglas-fir, the species the proposed project of this thesis would most likely use. Compression parallel to grain at

12% moisture content (the moisture level a piece is likely to be installed at) is 7,430 lbf/in^2. The same material's compression strength perpendicular to its fiber grain is 760 lbf/in^2. This means that this species of wood is only 10% as strong when compressed perpendicular to its fiber grain orientation as it is parallel to grain. The trend remains the same for all species of wood listed in this table.

Table 3- Tabulated strength values for select softwood species. Source: *Wood Handbook: Wood as an Engineering Material*

General Technical Report FPL–GTR–190

Table 5–3b. Strength properties of some commercially important woods grown in the United States (inch–pound)[a]—con.

Common species names	Moisture content	Specific gravity[b]	Static bending: Modulus of rupture (lbf in^{-2})	Static bending: Modulus of elasticity[c] ($\times 10^6$ lbf in^{-2})	Static bending: Work to maximum load (in-lbf in^{-3})	Impact bending (in.)	Compression parallel to grain (lbf in^{-2})	Compression perpendicular to grain (lbf in^{-2})	Shear parallel to grain (lbf in^{-2})	Tension perpendicular to grain (lbf in^{-2})	Side hardness (lbf)
Cedar—con.											
Port-Orford	Green	0.39	6,600	1.30	7.4	21	3,140	300	840	180	380
	12%	0.43	12,700	1.70	9.1	28	6,250	720	1,370	400	630
Western redcedar	Green	0.31	5,200	0.94	5.0	17	2,770	240	770	230	260
	12%	0.32	7,500	1.11	5.8	17	4,560	460	990	220	350
Yellow	Green	0.42	6,400	1.14	9.2	27	3,050	350	840	330	440
	12%	0.44	11,100	1.42	10.4	29	6,310	620	1,130	360	580
Douglas-fir[e]											
Coast	Green	0.45	7,700	1.56	7.6	26	3,780	380	900	300	500
	12%	0.48	12,400	1.95	9.9	31	7,230	800	1,130	340	710
Interior West	Green	0.46	7,700	1.51	7.2	26	3,870	420	940	290	510
	12%	0.50	12,600	1.83	10.6	32	7,430	760	1,290	350	660
Interior North	Green	0.45	7,400	1.41	8.1	22	3,470	360	950	340	420
	12%	0.48	13,100	1.79	10.5	26	6,900	770	1,400	390	600
Interior South	Green	0.43	6,800	1.16	8.0	15	3,110	340	950	250	360
	12%	0.46	11,900	1.49	9.0	20	6,230	740	1,510	330	510

The best practice in wood architecture is to align all forces parallel to the grain of the wood. Doing this assures forces travel through the strongest component of the material and do not rely on weaker lignin connections for strength. It is this principle that forms the basis for this project's structural system and therefore the entire design of the building.

4.4 Structural System Layout

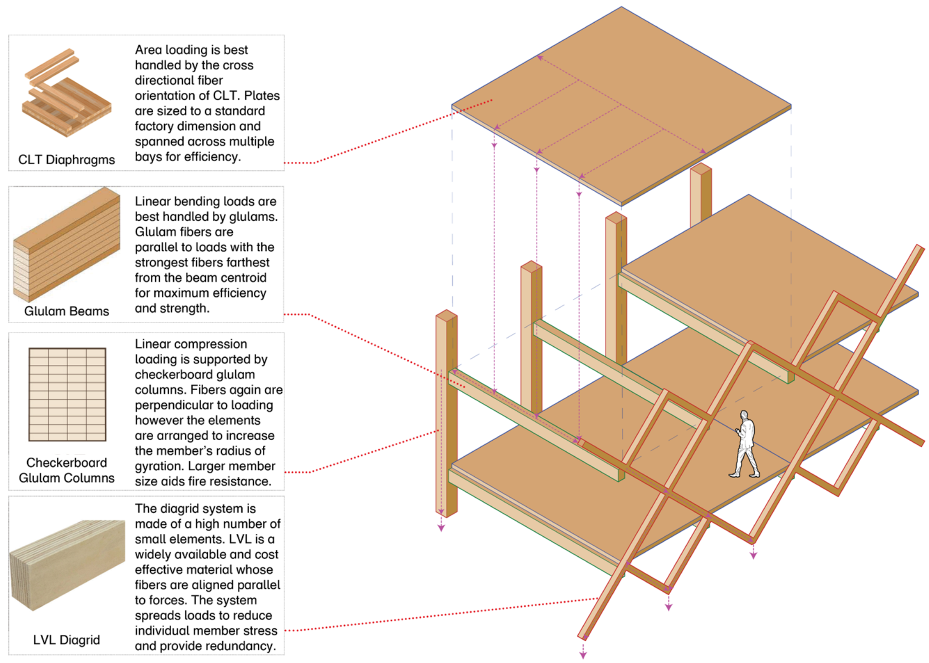

Figure 33- Base structural unit

Figure 33 shows the base structural unit this project is assembled with. It is completely based off the principles set forth in section 4.3, forces must be aligned for fiber grain direction. In many projects CLT is used throughout a structure. This is not necessarily a bad idea; CLT is a two way loading panel and as such can transfer forces from multiple directions. The issue however is that this is not efficient. Many of the forces moving through a building are not two way but rather linear, therefore much of the wood in the CLT is not engaged and is never used. CLT also occupies significant volume, interior spaces become more constricted and less usable. A material does not want to be used inefficiently or in a way that degrades the quality of spaces it encloses.

The system proposed for this project takes a different strategy. It matches forces to a specific engineered wood product. Table 4 gives a breakdown of the system.

Table 4: Specific force types are matched to specific EWP's

Table 4. Product to load type matching	
Load Type	**EWP Product Used**
Diaphragm	Cross Laminated Timber
Linear Bending	Glulam- Vertical Layup
Point Loading	Glulam- Checkerboard, LVL- diagrid
Lateral/Seismic Loading	LVL- diagrid, Glulam- struts

Let us start with an individual standing in the middle of the floor. The diaphragm loading imparted by them is handled by a CLT panel whose primary axis sends the majority of forces to glulam beams. Nail Laminated Timber (NLT) could be used here as a one way panel as well. The area loading is collected by the beams and is now a bending force. Glulam beams are well suited for this as they have a layup that places high strength lumber on the top and bottom of the beam. The ends of the beams are point loads that are supported by the diagrid and glulam columns. Glulam columns are extremely high strength members, transferring point loads parallel to their fiber grain. The layup of these members is checkerboard, and their thickness provides fire protection. The glulam columns run continuously through the building. Beams are hung off the columns or given ledges rather than pocketed in. This prevents unnecessary crushing forces on the beam ends. The other point load mounted to the diagrid moves diagonally through the connecting members. The diagrid system on the exterior of the building handles loading both vertically from the floor plates and laterally from wind and seismic shifts. Laminated Veneer Lumber is chosen for this system because while being a strong engineered wood product it is also a widely available, stock material. The diagrid has many elements, therefore using LVL is more economical. Diagrids work off two principles: the equalization and redundancy. Like a climbing anchor forces are equalized across two members, thereby giving each member only half the loading a single would be responsible for, as shown in Figure 34. They are redundant, if an individual member in the matrix fails, loading redirects through the rest of the system.

Figure 34: The ideals of a climbing anchor are the same in a diagrid system. Forces are spread equally between two supports. If one fails, the other still safely supports the load.

Loading is transferred parallel to the LVLs' fiber grain, thereby following the rule of best practice in wood construction. Due to the diagrid being a two way loading system the grid can support lateral loading just as easily as vertical. Finally, because the forces in the system flow parallel to wood grain, connections between members do not have to have to deal with high moment forces. Moment connections in wood are difficult to create and are better avoided all together if possible.

The diagonal members of this new tower are at 45-degree angles. The structural grid of the project is based on 12'x12'x12' units, therefore the members of the diagrid connect to each node on the outside of the building at 12' marks. This creates a modular system that is rather simple to fit program within. Apartment units occupy 2 or more of the 12’ bays. CLT is produced on 48’ presses, therefore a grid that fits in a common denominator of this size means assembly of the floor does not require custom sizes. This again assists in the economical aspect of this project. 12’ was chosen because it was not too far for CLT to span efficiently and not too small that its columns would be too tight to program within. 12’ became the sweet spot for the CLT panels and this number ended up being used throughout all dimensions of the structural system.

Lateral support does not only come from the diagrid system. Inside the building are three vertical circulation cores which themselves serve as lateral support. They are constructed from thick CLT panels with steel reinforcement. The three cores are positioned near the three outer corners of the triangular building where they are most effective. The central climbing wall of the building also is not just for show. A massive support core is integrated into the climbing wall. Using a truss like structure of thick glulams a rigid frame handles an immense amount of the lateral forces imparted on the building. CLT floor panels and the glulam beams of the floors all work to transfer forces to these lateral cores. The core also resolves the load paths of the inner section of the upper courtyard which would otherwise float in space above the main atrium and need a massive spanning system to support. Transferring forces straight to the ground is efficient and an excellent practice in wood architecture. The section in Figure 35 shows the lateral support core. Not diagonal cross bracing reduces the chances of these long columns from buckling under vertical forces and transfers lateral forces in the same manner the diagrid on the exterior does.

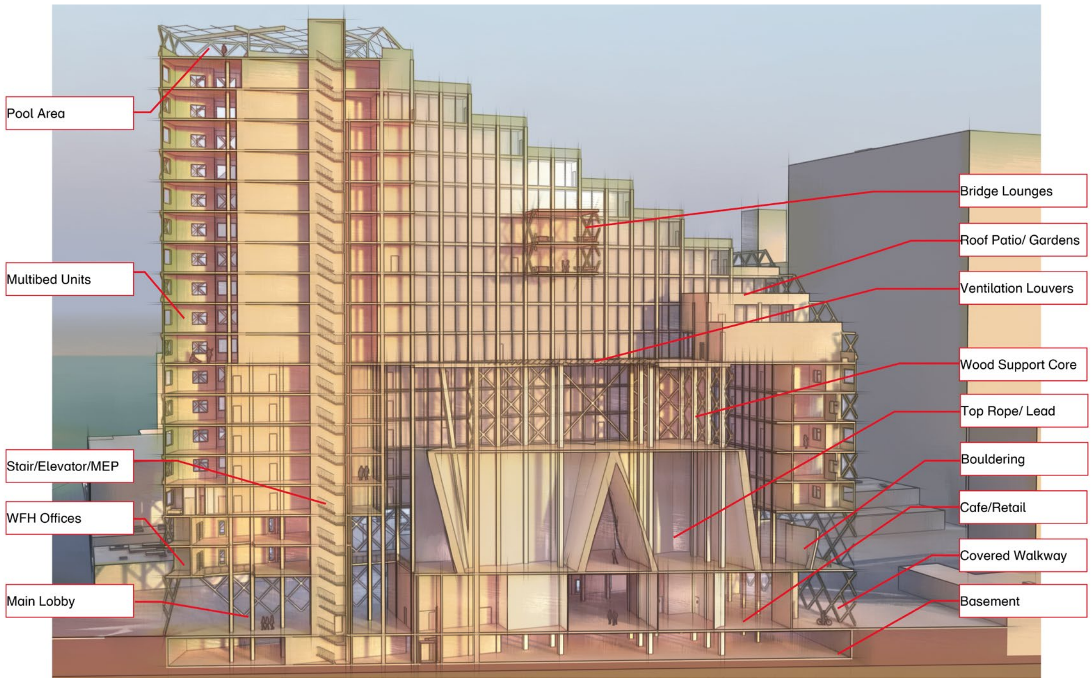

Figure 35- Longitudinal Section.

The foundation of the building will be a more conventional system, concrete footings and concrete basement walls. Large concrete abutments must be placed at the connections of the diagrid to the ground as well. As far as this thesis is concerned the ground conditions at the site are assumed to be acceptable or even ideal for a tower to be built upon it. That said, because the tower is made of wood its dead weight is actually far less than its steel and concrete neighbors and can thus be built on less ideal soil conditions. The tower lies near a retaining wall on the side of the Cherry Creek Trail; therefore, the lower dead weight of the building makes this an easier problem for geotechnical engineers to resolve.

4.5 Sustainable Building Systems and Strategies

As building is climate zone 5B the conditions of the environment do not oppose human comfort. Unlike residents of other parts of the US, Denverites do not have many complaints about the weather. Nevertheless, Denver experiences extremes of cold, heat, and wind. Norbert Lechner's book *Heating Cooling and Lighting* outlines three top climate responsive strategies in their order of priority (2009). First is to "keep the heat in and the cold temperatures out during winter." Second, "let the winter sun in." And third, "protect from cold winter winds." Lechner defines four lower priority yet still important strategies as well; "use thermal mass to reduce day to night temperature swings in the summer. Protect from the summer sun. Use evaporative cooling in the summer. [and] Use natural ventilation for summer cooling" (2009).

Wood as a material is somewhat conductive of heat making it a poor insulator. It is also not effective as a thermal massing material making the fourth strategy above difficult to attain. However, unlike a pure CLT building this project uses a space frame typology which allows exterior wall sections to be non-load bearing and therefore fully insulated. Figure 36, a photograph of Brock Common's construction shows how modular insulated units can not only increase construction efficiency but also allow for an easier continuously insulated envelope to be constructed.

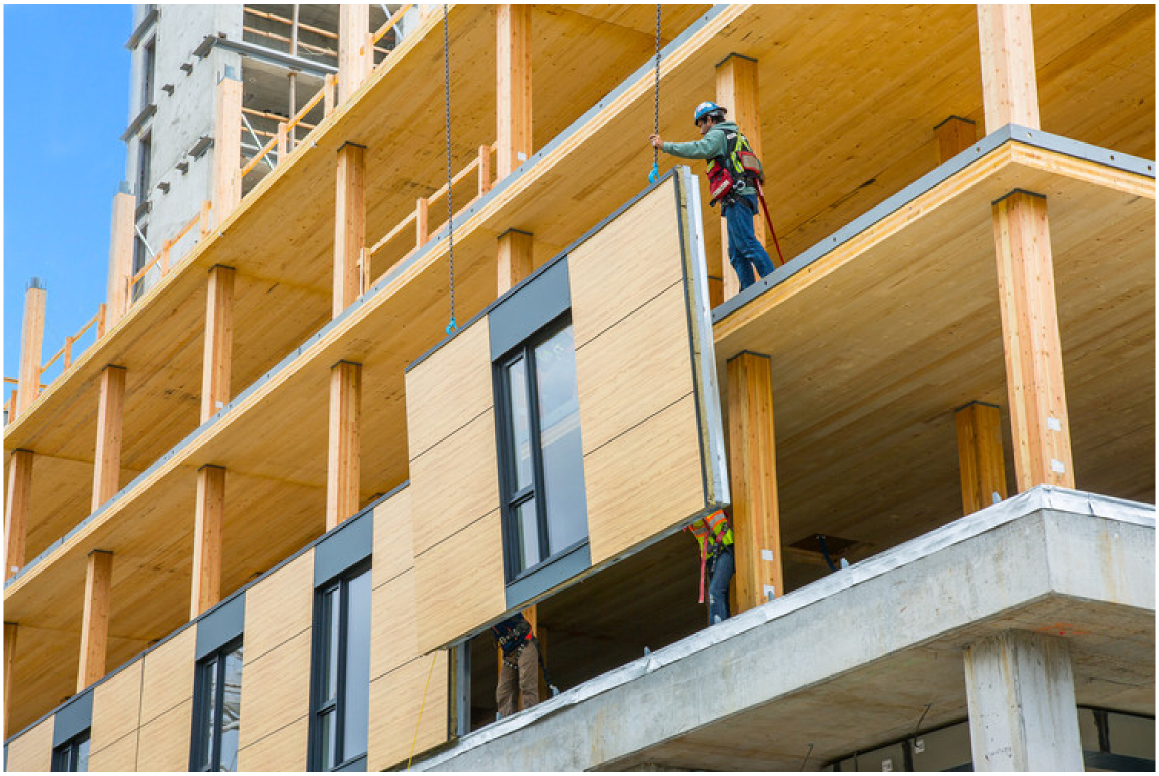

Figure 36- Preassembled walls are lowered into place on Brock Commons.

For the climate zone Denver is in, Lechner defines the recommended minimum R-values for building components as shown in Table 5:

Table 5: Components of a building in the project's climate need a certain minimum R-value for good building performance. Source: *Lechner 2009*

Table 5: Required component R-Values in Denver's Climate					
	Ceiling	Walls	Floor	Slab Edge	Basement
R- Value	R50	R20	R25	R10	R15

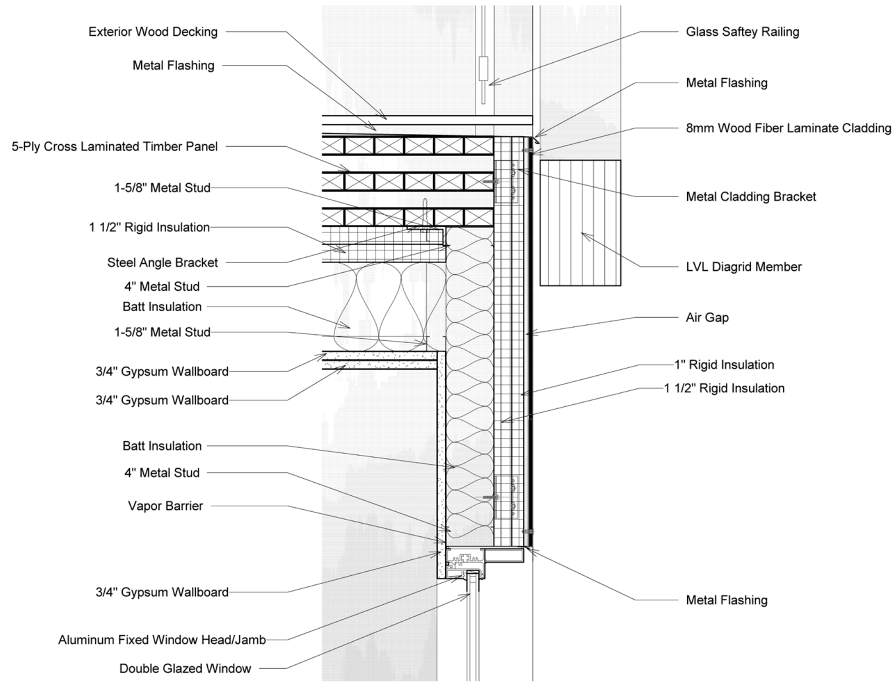

Figure 37- Example wall section

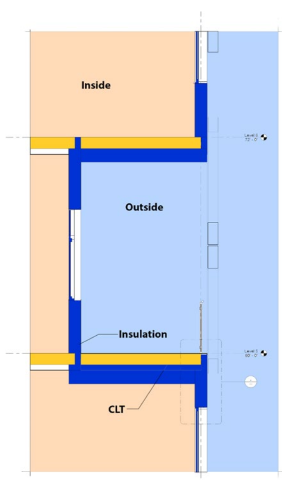

Figure 38- CLT panels are split and insulation runs continously.

Figure 37 shows a typical unit wall section. The walls reach R20 and the ceiling reach R50. The CLT panel here is encased in rigid insulation to prevent thermal bridging. Due to the span direction of the CLT the panel can be broken in strategic areas to further prevent thermal bridging issues. The wall units are framed in light frame steel and can be slotted into place behind the diagrid system. Figure 38 shows how insulation will run continuous as a result of panel breaks.

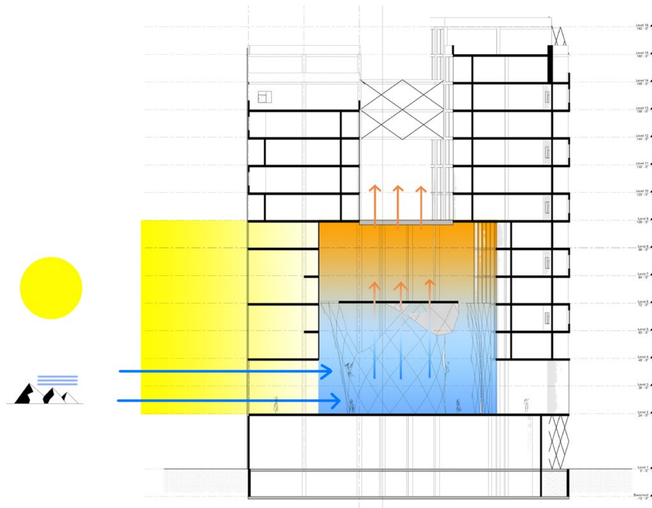

Figure 39- Passive ventilation diagram

Ventilation is an important factor in the design of gyms, and climbing gyms are no exception. The top of a climb can become significantly hotter than where the climber started; not to mention moisture, heat, and chalk dust output from the climber. Furthermore, the large spaces required for climbing gyms make mechanical systems difficult to design. To a climbing gym's advantage however, especially one such as that being proposed in this thesis, a high temperature gradient creates a stack effect that can drive passive ventilation. This thesis design proposes to take cool mountain winds, introduce them into the lower section of the gym, and allow stack effect to push air upwards through the building and out into the courtyard on the 9th floor, shown in figure 39.

4.6 Architectural Design

The following section outlines the architectural design of this project.

4.6.1 Building Massing

Wider bases lead to improved lateral support as well as maximum usage of land for revenue generation. Therefore, the building occupies nearly the entire site. Figure 40 diagrams the massing study. The first step in massing was to extrude the base of the site upwards by one story. This would create the entry and commercial facades. Next the upper levels were cantilevered out over the sidewalk to create more space to work with and to create a welcoming covered sidewalk. This now wider offset base was then extruded 80 feet upwards. This was to be the original height of the main climbing wall. The center of this mass was hollowed out to create the large space for this wall. Much later in the design process the height of the gym wall was lowered to 40’ but the open space remained the same. Next more levels were added above to bring the building to 18 stories. Each level was made to be 12’ high and match the horizontal grid spacing. Again, the center of this mass was hollowed out, this time for light and air. Finally, to break up the imposing mass of the building and allow light and air to reach the neighborhood behind the building the mass of the building was stepped back. These steps were each two structural bays long and moved away from the south corner of the building. This opened the entire upper-level area to the south allowing sun and air access. These stepped back sections created a large amount of usable roof space which was given to all residents of each level. To break up the very tall courtyard a double story bridge lounge was also introduced. This bridge also allowed an egress path for the residents of those floors without extending stair cores through roof gardens. Figure 41 is the finished product.

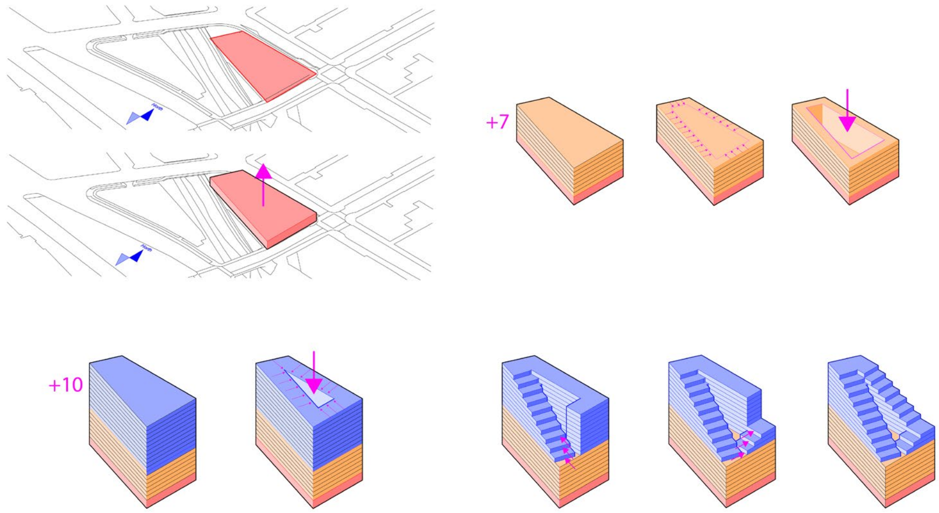

Figure 40- Massing Study Diagram

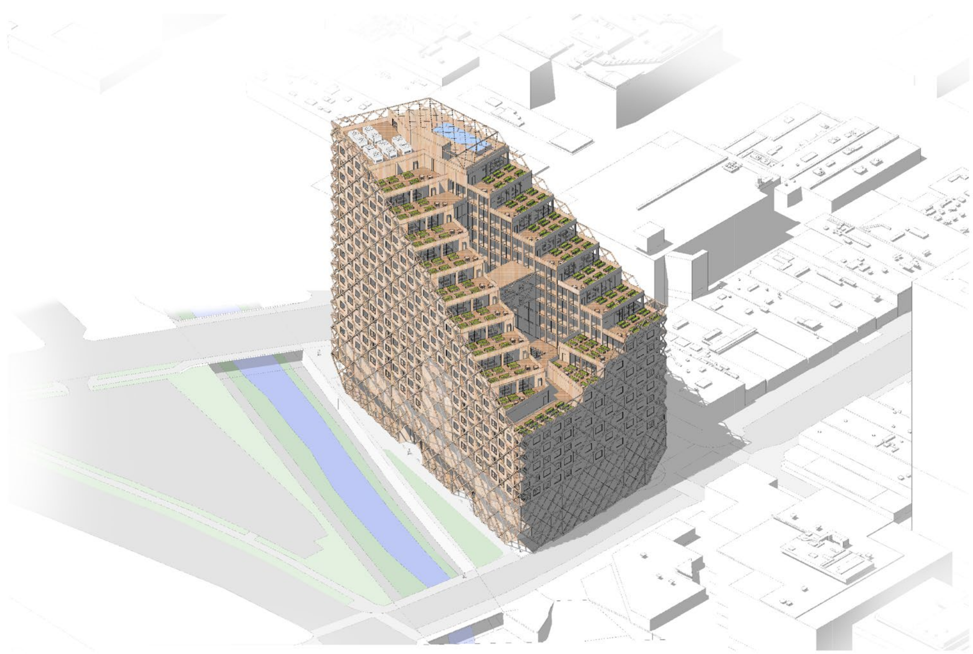

Figure 41- 3D Isometric view of the tower

Each apartment unit has a balcony and a large window. To break up an otherwise boring façade the position of the balconies is alternated floor by floor to create a checkboard pattern. The diagrid elements only cross in front of balconies and do not cross in front of the large windows. At the ground, the diagrid is peeled open at major entry and exit points.

4.6.2 Site Response

The site sits on a boundary. The dense urban core meets a sunken river and then an imposing wall of busy roads. Typically, this would mean few visitors would wander over. However, the river itself is an attraction because it is a beautiful green walk and very effective foot and bike connector to the rest of the city. The site abuts directly onto this river and sits across the street from a very well designed access point. A ramp access point also exists just adjacent to the north west corner of the site. On the other side of the site is the cultural heart of Denver, the LoDo neighborhood. Visitors walk up and down this street year round. Therefore, the site has the potential to become an extension of that downtown procession and to become a filter in the link between LoDo and the river walk. This potential for excellent public engagement makes this site perfect for commercial ventures to set up shop, especially along the path between LoDo and the river entry point. Therefore, the special arrangement of the first floor of this thesis' proposed structure directly responds to the circulation pattern of the site (Figure 42-43).

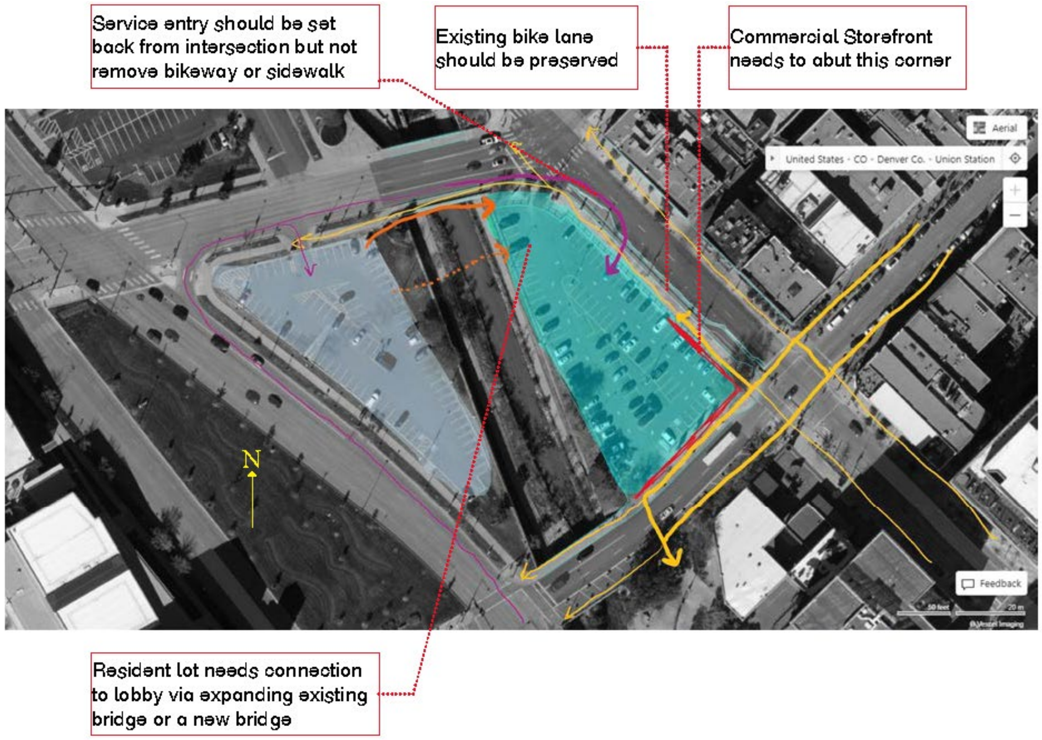

Figure 42- Circulation diagram of project site and proposed responses.

4.6.3 First Floor Plan

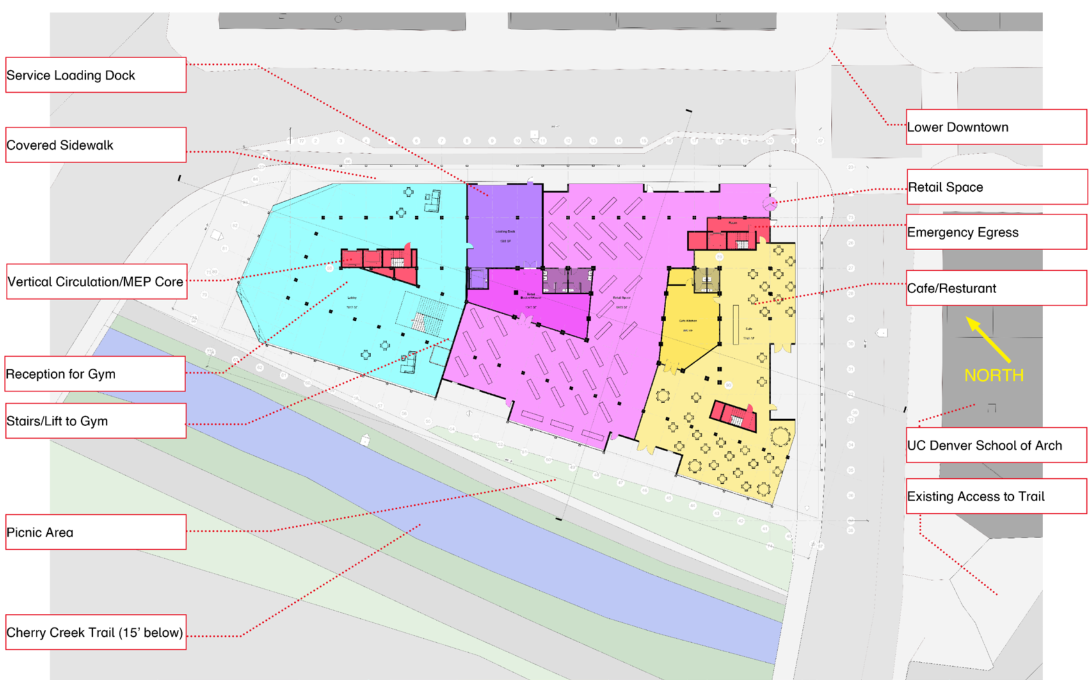

Figure 43- First Floor plan and adjacent site.

Along the outside of the building the diagrid meets the street level on the edge of the existing sidewalk. The second floor rests above this and creates a large, covered sidewalk. Covered sidewalks become very welcome items in periods of bad weather, blistering heat, and relentless sun the latter of which is very common in Denver. A covered walkway draws in people, a very important need for businesses. The corners of the diagrid are opened out to act as dramatic gateways for people to enter and exit the covered walkway.

The first floor, shown in Figure 43, is made of 5 main components. Inside of each corner of the triangular site are vertical circulation cores which continue up through the building. These house stairs, elevators, and MEP systems. On the south end is a café/ restaurant with a grab and go counter and coffee shop style seating in one section and restaurant seating down lower. The interior core, composed from the main lateral core of the building, houses the kitchen and fridge. These spaces receive a lot of light and doors are provided on the river side façade that could allow for outdoor seating in warm months. The center section of the building is given to a commercial retail space. Its entry directly sits at the site's most busy pedestrian intersection and is given a display window to capture passerbys' attention. The space runs continuous through the building and is 20' to allow light in and remain comfortable for visitors. Racks in Figure 43 are shown at angles to create an exciting retail space however the space can accept any display orientation. Again, the main lateral core of the building is used to house back of house fittings of the retail space. The loading dock, shown in purple, will be explained more in section 4.6.7. The north end of the building houses the glazed main lobby of the building. The diagrid, as mentioned, is lifted in the corners to create a dramatic entry point. The glazing follows suit, and the doors are built into this exciting, angled face. The main vertical circulation core partitions this lobby between residents and users of the climbing gym. The elevator bank faces outwards and allows residents a straight path from door to door. The north west section is the lobby for the climbing gym, with a reception desk and a form of controlled access so that unauthorized people have a harder time making it up to the gym. Around the perimeter of the lobby are spaces for couches and chairs that can be used for waiting, meeting, or 'alone-together' space. The most interesting aspect of the lobby is its opening to the main climbing gym, those entering are allowed a peek through this opening into the vast gym (Figure 44).

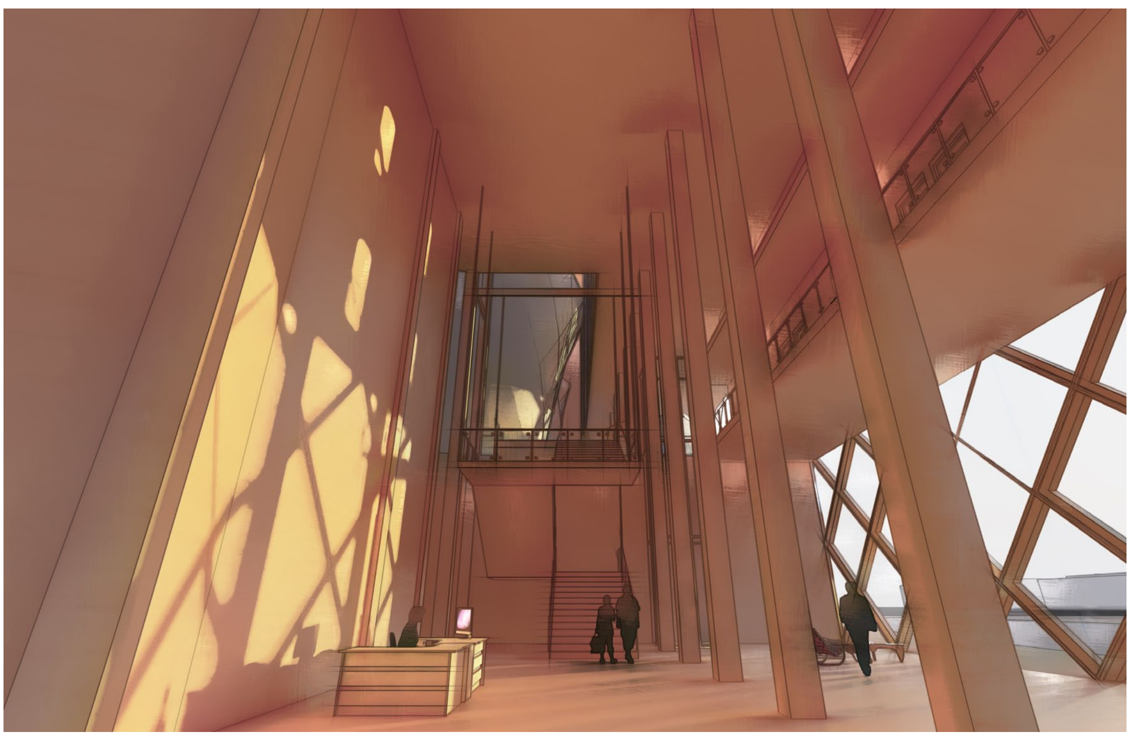

Figure 44- Interior perspective, the main lobby.

4.6.4 Second Floor

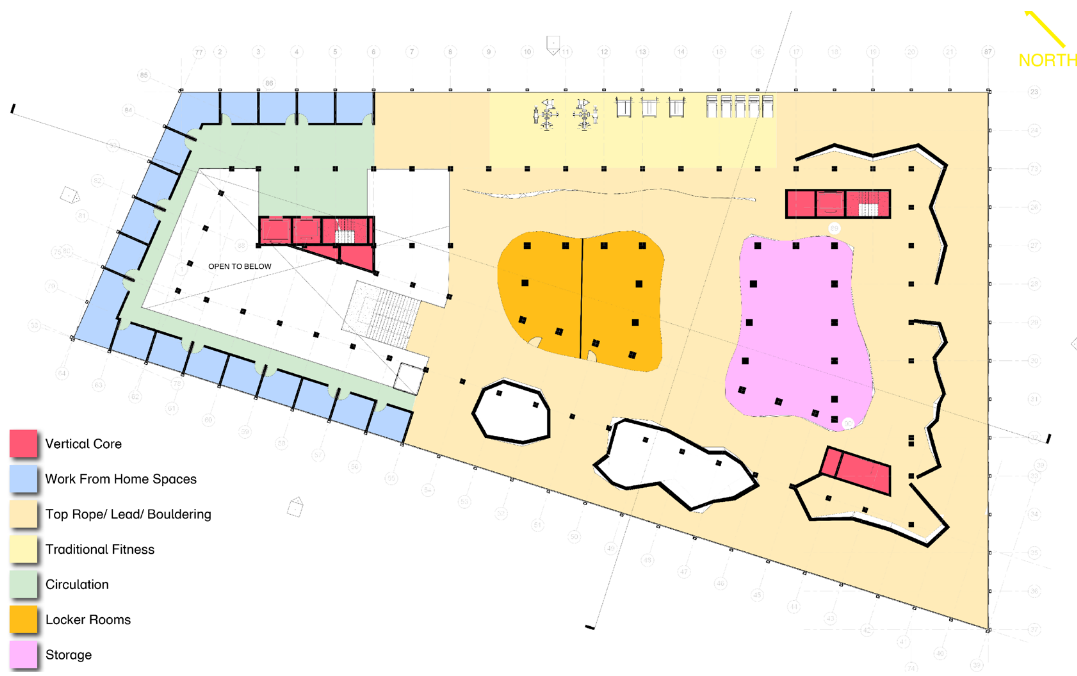

Figure 45- Second Floor Plan

As shown in Figure 45, the second floor is dominated by an indoor climbing gym. A monumental staircase (or adjacent elevator) takes climbers up from the lobby to this massive and exciting feature of the tower. This double height space offers 40’ of roped climbing, including an overhanging lead cave. Around the perimeter are bouldering walls of both slab and overhanging composition. All walls are glazed to allow maximum daylighting. On the north end is a conventional gym section, still a needed part of a climbing gym. The central lateral core of building supports the climbing wall, the wall itself is shaped like a lowercase “n” with two bases that connect in an overhang. The overhangs are fun to climb and falls from them generate large swings that require more space for safety. Inside the climbing wall are the locker rooms and storage rooms. This space usually goes unused in climbing gyms, here where all space is valuable, they become very useful. The north end of the building is a series of small work from home offices. In a post pandemic world such spaces have become much more relevant with many companies seeing the benefits of allowing remote work. Residents are now provided space in which to work from home without having to work inside their home and give up space for office. In its current form the cubicles are intended to be accessed by keycard only so that members of the general public may not access the spaces. Because the climbing gym occupies two stories a third story of work from home offices is built above the first row. 36 offices are provided in total including 4 larger collaboration sized units.

Likely the most striking feature of the main atrium is the climbing wall. Colorado has a deep history of climbing, almost as strong as its skiing roots. The state features many classic routes such as the Petit Grepon and popular destinations such as the Flatirons. Including this exciting aspect of the building's context in the life of its occupants seems all too appropriate. The main unit of the climbing gym is a multistory arch with a mixture of slab, face, and overhanging climbing. A height of 40' was appropriate. Too short and the climbs are frustratingly quick, likely doomed to become extended bouldering problems. Too high and climbers will spend long amounts of time on route leading the others having long wait times for routes and belayers becoming bored. Surrounding the main wall are lower bouldering walls. While the origins of bouldering lie in practicing for longer routes it has become its own popular form of climbing with some devoted entirely to the practice. Many climbing gyms, including this one, feature more bouldering routes than roped climbs for the convenience of climbers who may not have a partner, desire a non-endurance workout, or fear heights. Around the gym are benches and other gathering spaces. Climbing is a community driven sport with groups watching, challenging, and encouraging each other to push their limits. Climbing brings people together where a traditional gym wouldn't or couldn't (Figure 46).

Figure 46- An individual effort is not done alone while climbing.

4.6.5 Fourth Through Eighth Floors

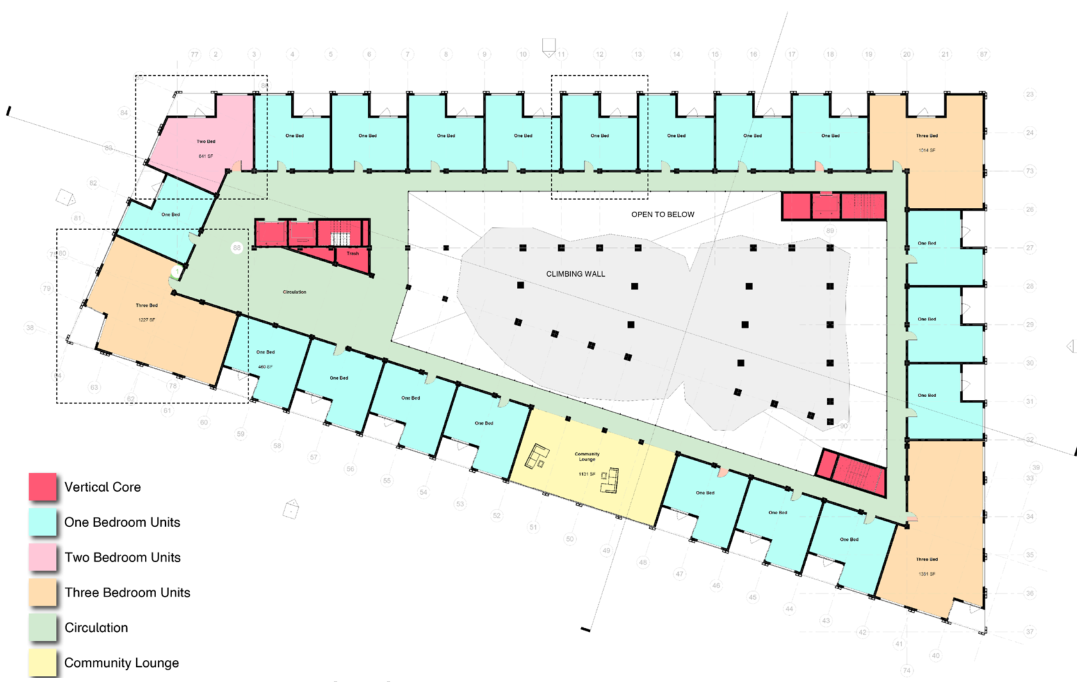

Figure 47- Typical floor plan, 4th – 8th floors

The fourth through eighth floors follow a typical donut typology of housing. For maximum access to light and air the dwelling units face outwards on the periphery with services on the inside. However, the center that would typically be dark and hard to program is fully engaged in the form of the climbing gym. The gym wall and central lateral core reach upwards through this space, flanked by walkways that ferry tenants to their units. These walkways cantilever 6' out from the inner grid line of the plan and do not require additional support below, freeing space below. The walkways are glazed to reduce noise and ease fire restrictions. Figure 47 shows the 12' grid that the building is assembled with. Apartment units are fit into two of these grid lines and are 24' feet deep. The corners which do not comply with the regular gridlines are made into the 2 bedroom and 3 bedroom units. Unit descriptions will be elaborated on in later sections.

On the western façade of the building two apartments are deleted to create a path of light from the outside to the climbing gym. These are turned into two story spaces and become community lounges for two floors of residents to enjoy. The odd numbered floors have a catwalk to continue circulation, it looks down into the lounge. This creates a functional and exciting space. Three vertical circulation cores provide egress and services to each floor. The largest core also has a garbage chute that runs to the basement.

4.6.6 Ninth Through Eighteenth Floors

Figure 48- Twelfth Floor Plan

The upper floors are characterized by the stepped back massing of the building shown in section 4.6.1. The ninth floor marks the bottom of the massive outdoor courtyard. The center contains the louvers used by the atrium below for ventilation and provide views down from above. The southern corner contains the large community space for this level. Upper levels have two sets of greenhouse and outdoor gardening/ gathering space. Figure 48 shows level 12's arrangement with the gardens capping two wings of the plan.

The gridlines on the upper levels are still 12' on center and there is an opposing gridline 24' in. Now however, there is an additional gridline another 24' inwards. This new row of columns resolves directly to the ground by meeting with the lateral stability core of the building. The section in Figure 49 shows this inner column grid resolution.

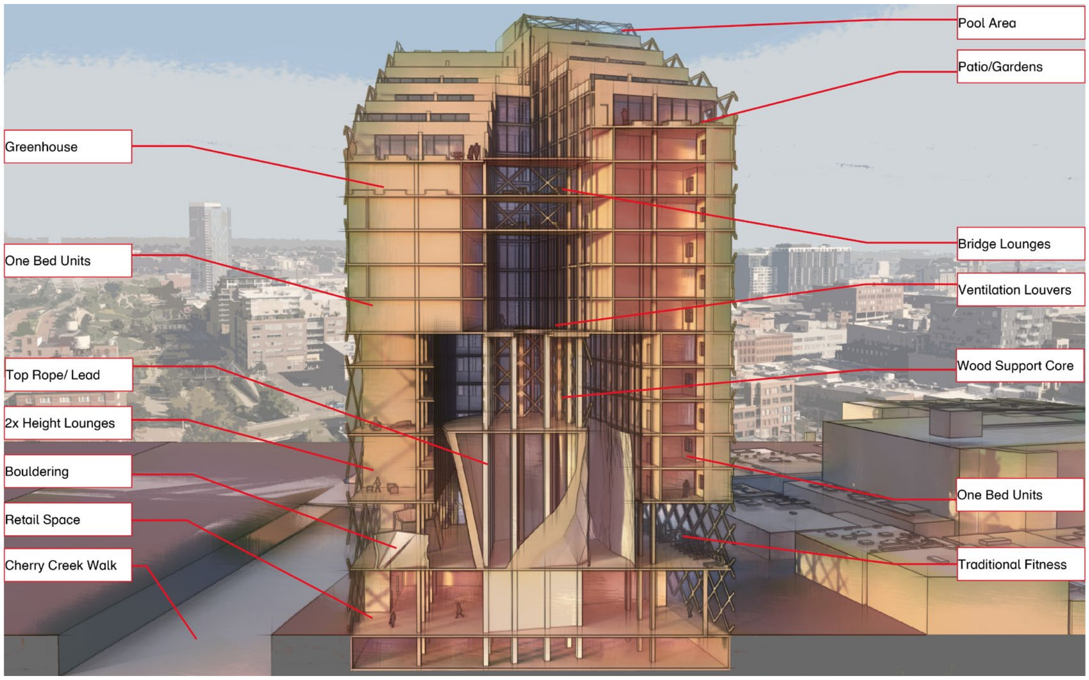

Figure 49- Lateral section of the tower.

This direct system, while perhaps not as dramatic as a system like the zipper truss of the UMass Design Building, is highly efficient. There are fewer complex forces and more linear, parallel to grain, forces for the wood lateral core to support. This falls in line with the best practices that this thesis has laid out in previous sections.

An inner grid line of 24’ also means that a 24’x48’ CLT panel fits perfectly into the grid. As mentioned earlier typically CLT presses are this size therefore making this a ‘stock’ size, increasing economic efficiency of the project.

In the center of the 12th and 13th floors, to break up the large courtyard space, is a two story bridge lounge. This is a communal space, great for when the outdoor spaces aren’t comfortable. They also act as a path of egress for these floors who only have two of the three vertical cores and would otherwise be too far from them for safe fire egress.

4.6.7 Rooftop

The roof of the structure includes a pool with a covering that can be opened in summer and closed in winter. The pool is fitted to the grid below to provide a direct load path to the ground. The rest of the roof is given to HVAC systems that most likely will need space.

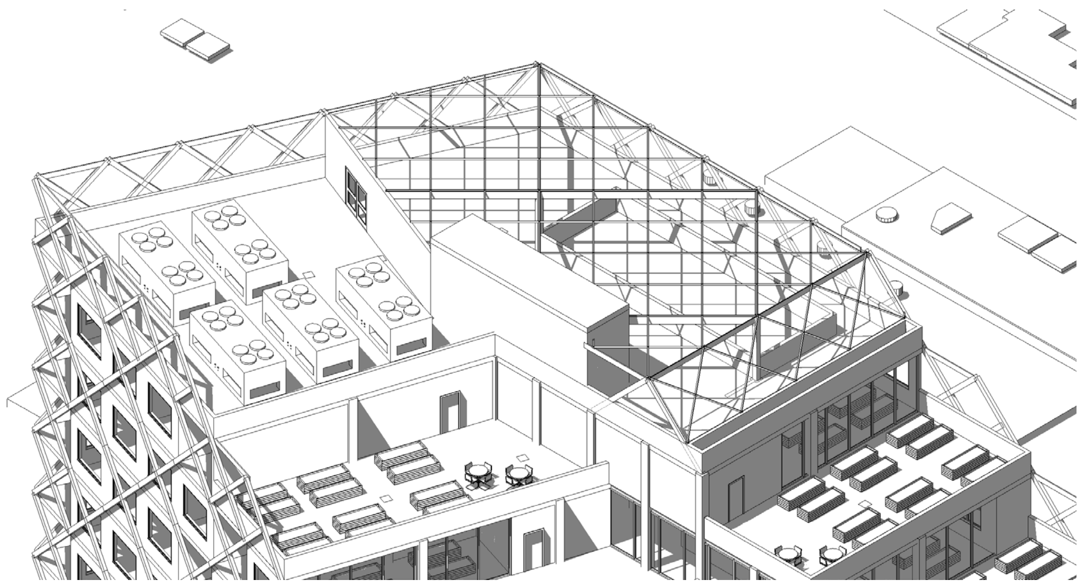

Figure 50- Rooftop Pool and HVAC

4.6.8 Residential Unit Design

The residential units in this project are designed for young professionals, who make up a large portion of people moving to Denver. Therefore, units can be small. The majority of units in this tower are single bedroom units. The multibed units are designed for unrelated individuals or young couples with multiple bathrooms, large common areas, and large closets. Throughout the project all units have a balcony to connect the occupants to the outdoors in a private setting.

On the 4^{th}-8^{th} floors the single bed units that make up most of the floors are 460 square foot micro units (Figure 51). As with all the units in this project the design philosophy behind unit design was to give bedrooms a window directly to the outside, a connected living room and kitchen also with an outside window, and the bathroom in inside of the unit not in need of sunlight. Kitchens could also be placed farther inside the unit away from a window. For how small the square footage of these units are the room sizes are still quite comfortable for an occupant. The bedroom is 10’x12’ with a walk in closet. An MEP space is at the back of this closet. The main room featuring the living room and kitchen is 12’x24’ and has a sliding glass door that leads to a 7’x12’ balcony. The bathroom is 7’x8’ and with some modification can be made ADA accessible along with the rest of the unit. This compact design is meant to have a lower rent and make room for the amenities that make the building special. However, the unit can still fit elements such as a queen size mattress and a fully equipped kitchen. The design also calls for the main room to have exposed CLT ceilings, MEP can fit into a drop ceiling over the other half of the unit. This is doable thanks to a 12’ floor to floor height and, due to short spans, a thin CLT floor plate on each level.

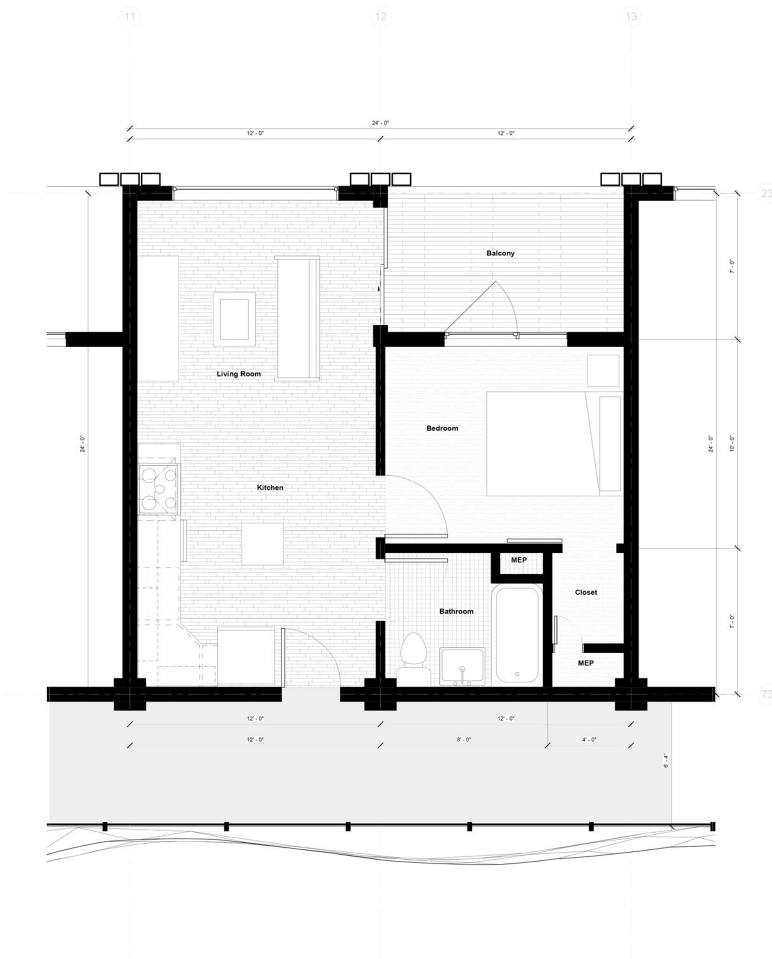

Figure 51- 4th through 8th floor typical one bedroom unit floor plan

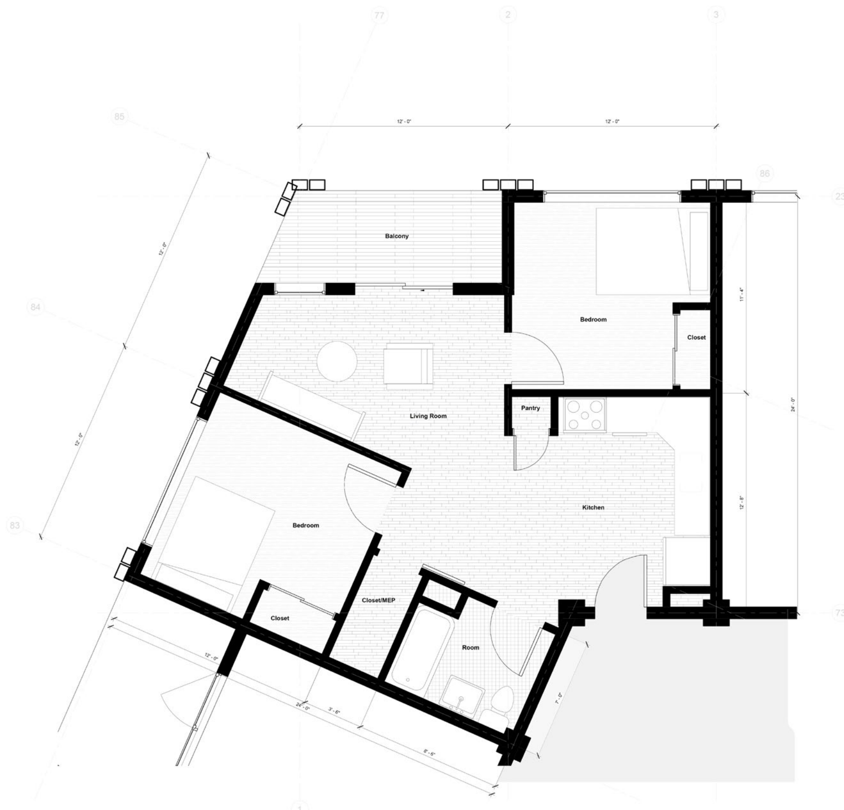

Figure 52- 4th through 8th floor typical two bedroom unit floor plan

The two bedroom unit is built into the north corner of the floor (Figure 52). The arrangement works well because it does not force the deletion of adjacent one bedroom units yet has enough room for two 12’x~12’ bedrooms. The kitchen in this unit is moved into the back yet still is fully equipped. The bathroom is large than the one bedroom units and the closet space is very generous. Each bedroom gets its own closet as well. The living room abuts the outside wall of the building and features a very well sized balcony.

Figure 53- 4th through 8th floor typical northwest corner three bedroom plan

The other corners of the building are 3 bedroom units. Figure 53 shows an example of one of these units. They are designed for three unrelated individuals. There are two entirely separate bathrooms allowing for multiple simultaneous users. The kitchen and living room are wrapped into an interesting “L” arrangement and the kitchen is given a bar style seating. This “L” wraps around a generously sized balcony and faces the Colorado Front Range. This space is meant for socialization. There are two large storage closets in addition to each bedroom receiving a closet.

On upper stories larger floor plates allow for large units. Still all the units conform to the grid system and the majority of units are one bedroom units.

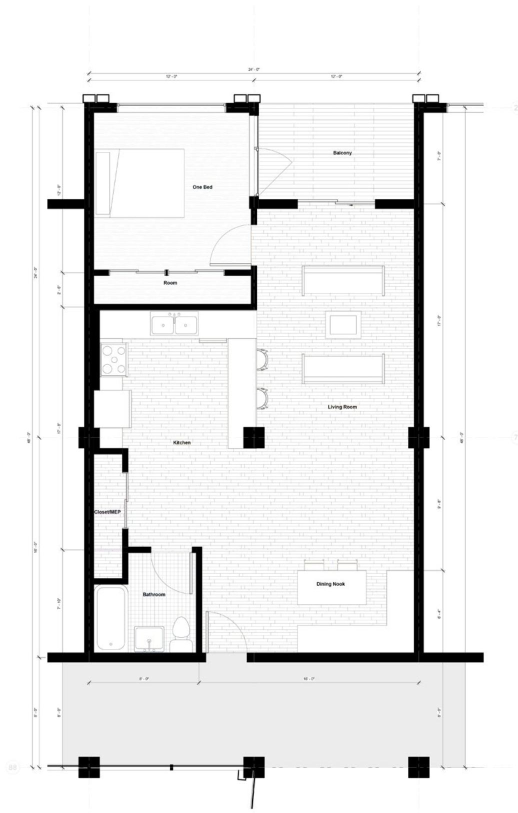

Figure 54- 9th through 18th floor typical one bedroom unit plan

The typical one bedroom unit for these floors, shown in Figure 54, is about 830 square feet and features a large bedroom, U shape kitchen with bar seating, and a dining nook. The bathroom is ADA accessible but not oversized considering the number of occupants of the unit. The unit is great for either a well to do young professional who wants a bit more space or a young couple wishing to stay downtown. The center of the unit has a column in it. This column not just integrates with the kitchen but is meant to be left exposed to connect the occupants to the materiality of the building. This is an important feature on any timber building.

CHAPTER 5

PROJECT ECONOMICS

6.1 Project Economics

The following section gives a brief overview of the economics of the projects and its tangible and intangible benefits.

6.2 Materials and Construction

Table 7: Data from Laguarda-Mallo, Espinoza, 2016 shows cost comparison of wood vs steel/concrete

Element	Concrete/ Steel option	CLT options			
		Basic CLT option 1	Basic CLT option 2	Green option 1	Green option 2
	(Concrete walls/roof, steel beams, light-steel frame)	(CLT walls/roof, steel beams, light-steel frame)		(CLT walls/roof, glulam beams, wood-frame)	
Structural Walls	$1,071,680	$624,417	$414,901	$624,417	$414,901
Concrete Slab	$256,416	$256,416	$256,416	$256,416	$256,416
Roof System	$600,975	$427,809	$289,339	$427,809	$289,339
Interior Walls*	$155,304	$155,304	$155,304	$297,666	$297,666
Steel Beams	$506,575	$506,575	$506,575	-	-
Glulam Beams	-	-	-	$29,022	$29,022
Extra CLT Walls	-	-	-	$115,407	$84,977
Extras for CLT**	-	$595,241	$595,241	$654,768	$654,768
TOTAL $	2,590,950	2,565,763	2,217,777	2,405,506	2,027,091
SQFT	40,065	40,065	40,065	40,065	40,065
Cost per sqft	$64	$64	$55	$60	$50

* Interior walls for concrete and basic CLT options are in light-steel frame construction. Interior walls for CLT Green options are in wood-frame construction.

** Extras for CLT includes labor cost and connectors for CLT

A major factor in any project is cost. In a real life scenario, the deciding factor of whether a project such as this would be constructed in wood or not will depend on its economic performance. While an argument for the economy of wood vs steel and concrete is not the focus of this thesis it is a topic worth mentioning. In the paper Cross-Laminated Timber Vs. Concrete/Steel: Cost Comparison Using a Case Study a design for a theatre in Napa, California was quoted in steel/concrete, hybrid wood and steel, and fully wood. The findings show CLT proved cheaper than steel in the project, “the cost evaluation for the performing arts center showed that CLT would signify a cost reduction of up to 21.7% in the cost of structure, depending on the extent to which CLT is used in the building and the manufacturer selected” (Laguarda-Mallo, Espinoza, 2016). As shown in Figure 58, the cost of CLT quoted in this project was as low as $50 a square foot, compared to the traditional option, almost 22% more expensive at $64 a square foot.

Wood is economical because of several factors. For one the material itself is cheaper than steel or concrete (Table 7). Wood is also much lighter than its analogs. Foundation systems, typically a very expensive factor in construction, are reduced as the overall weight of a finished building is reduced. This can become especially relevant in regions where soil conditions are poor for construction. Transportation to the site requires few trucks and gas. On site due to the member being lighter they are faster, easier, and safer to assemble on site. Mass timber is typically designed as an assembly of prefabricated parts. Erection of a structure is far quicker than other forms of construction as the workers simply assemble from prefabricated parts like a giant Lego model. Labor time is reduced as well as overall build time. This saves a project 20% in schedule related costs and between $5.81/sf and $10.93/sf in area savings. Of note, none of the projects that were analyzed in the case study reported major jobsite accidents (Smith et al. 2018).

Sourcing lumber for this project is actually quite easy because of its proximity to the largest sources of timber harvesting in North America. The western US and Canada hold millions of hectares of forest land, and Denver finds itself within a few hours drive of large engineered wood operations in Idaho. The sheer scale of forest land in the US and Canada means that the volume of wood consumed by a project such as this is grown back in mere minutes (McLain, 2018). Close proximity of materials sourcing leads to lower transportation costs and lower environmental impact.

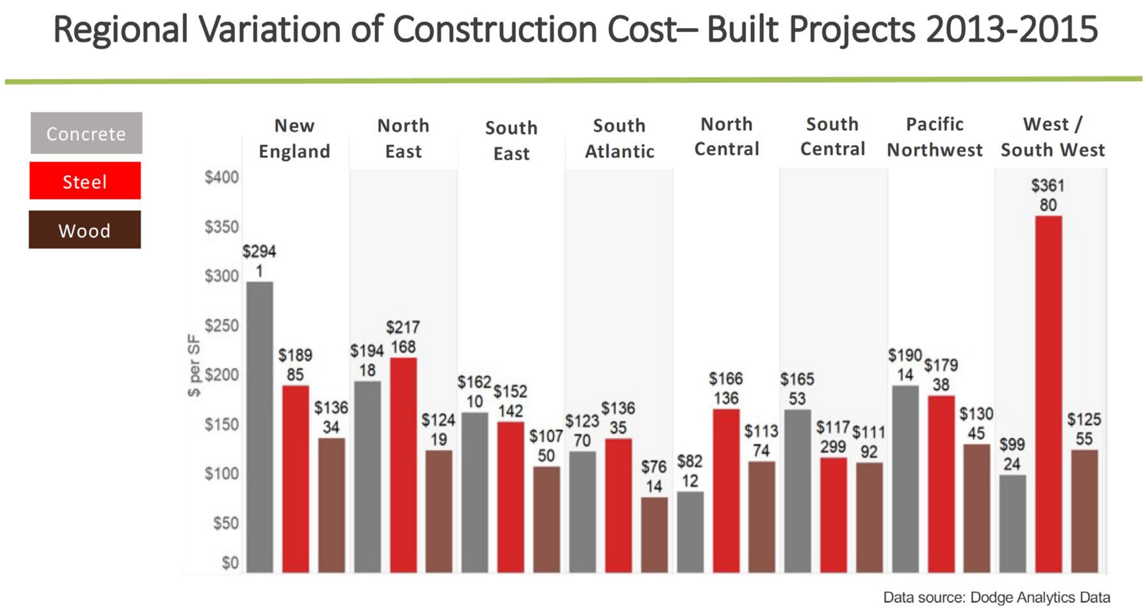

Figure 55- Regional average construction costs per square foot by material

As shown in Figure 55, cost per square foot in the Denver area (West/ Southwest) steel construction is enormously expensive compared to concrete and wood. Concrete, according to this data comes in slightly cheaper than wood (McLain, 2018).

U.S. Costs per Square Foot of Gross Floor Area 2021

CUMMING
Building Value Through Expertise

West | Midwest | South | East

	Denver		Chicago		Nashville	
RESIDENTIAL						
Single Family Detached-Medium Quality	$383	$115	$353	$294	$258	$215
Apartment/Condominium-Mid Rise	$314	$133	$534	$411	$390	$300
COMMERCIAL / OFFICE						
Single Story	$203	$135	$399	$332	$291	$243
Mid-Rise	$293	$216	$795	$663	$580	$484
High Rise	$485	$345	$914	$761	$667	$556

Figure 56- Data for Midwest construction cost/square foot as of 2021.

Figure 56 shows construction costs per square foot as of the time of this thesis' writing. None of the categories in the data match the specific building type of this thesis so we shall use the higher end cost/sf of a high rise office building, $485/sf (Shetty, 2021). At the time of this thesis writing lumber prices have skyrocketed. However, according to estimates “As we hit mid-year, we do expect a normalization of material price increases and those that have plateaued at the beginning of the year will close the gap over the next three to six months” (Domestic Material Price Trends | Cumming Insights - Construction Market Analysis, 2021). The total gross square footage of the structure proposed by this thesis is 491,949 square feet. According to Cumming’s data this building will cost $238,595,265 to construct.

Unfortunately, Cummings does not specify which material choice is used in their calculation of this number. More information on steel specific construction costs is harder to come by an exact comparison between steel, concrete, and wood is not available without an expensive subscription to services like R.S. Means. However, because most if not all building in the commercial high-rise sector is done in steel and concrete currently, it is safe to assume for the purposes of this these that the quoted value, $485/sf, is for these types of construction. Thus, if we then use the 22% reduction in cost that was determined earlier in this paper, we can calculate the cost of this structure in mass timber. This building would cost $395/sf and $195,569,890. A savings of $43,025,375.

6.3 Building Valuation

The other factor in mass timber that goes beyond simple materials and construction is valuation of the structure. A timber building itself has a series of ‘intangible’ values that lead to a higher quality product (McLain, 2018). On the surface is the mental benefits associated with human’s innate bio-phila and creating a living environment that directly connects occupants to natural materials. Stress and anxiety reduction, better overall health, and higher productivity (Figure 57) have been linked to mass timber architecture. (Health Benefits of Wood, 2021).

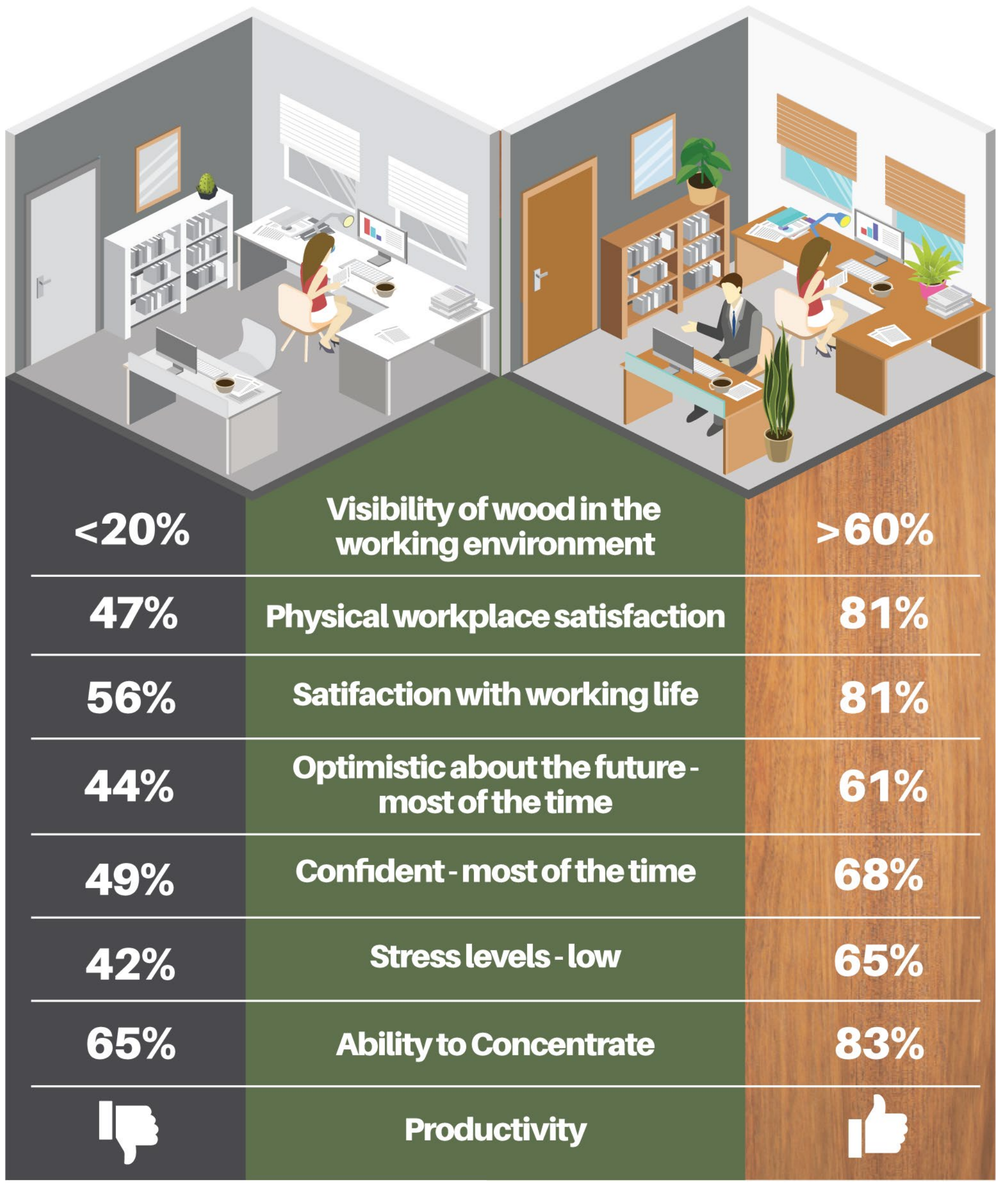

Figure 57- Survey of occupants in non-wood and wood architecture.

Another source of 'intangible' value of a wood building isn't fully intangible to the world, that is a wood structure's environmental impact. As mentioned earlier a mass timber building has a much lower impact on global CO2 emissions than a steel building.

Steel consumes massive amounts of energy; mining, ore extraction, smelting, transportation, on site assembly, and melting for recycling are some of the aspects of using steel that contribute to its massive carbon footprint. Concrete, while not as bad, is still very heavy to transport and uses intense amounts of fresh water in its creation. Some atmospheric carbon is stored in concrete. Concrete is very difficult and energy intensive to reuse. Wood is grown from trees which absorb CO2 from the atmosphere to create its own cellular structure. In the process oxygen is released. Wood is, as mentioned before, lighter to move and handle which saves CO2 in those aspects. Mass timber elements are easy to reuse so as long as holes aren't redrilled. In the end whatever energy a mass timber element needed in its creation is still far offset by the carbon locked in its body (Figure 58).

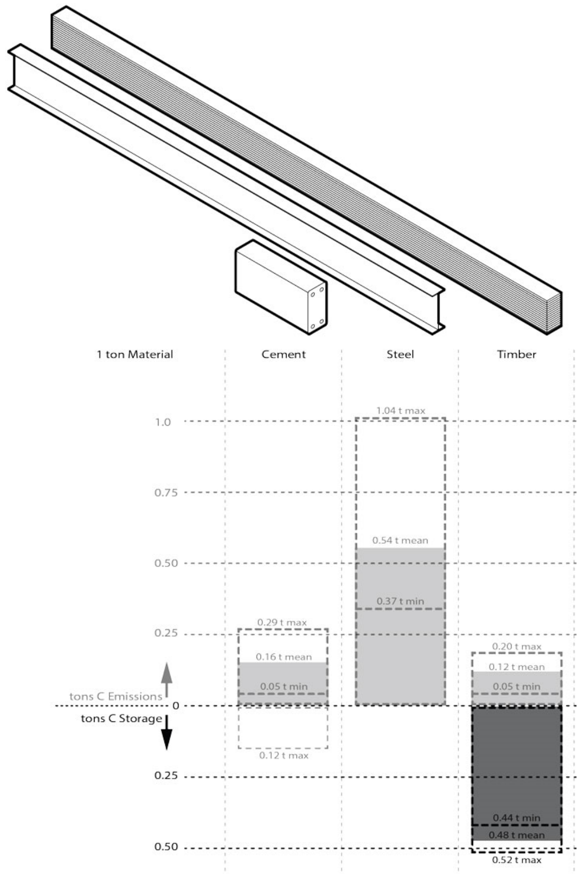

Figure 58- Carbon profile of wood, steel, and concrete by weight

What does this have to do with valuation? In modern times it has become very clear to the general public that climate change is a real threat. Therefore, as a society we have begun to value products which in some way help mitigate the climate crisis. This sustainable market has become a force to be reckoned with and has become a target of which to market to.

The aesthetics, health benefits, and environmental impact of wood architecture has led to a direct financial benefit for developers and building owners. It has been shown that tenants in a mass timber building are willing to pay an extra $7 per square foot of rented space than a similar non-timber building in the same market (Benefits of Using Wood in Construction, 2021).

6.4 The Bottom Line

Lower cost per square footage for construction, quicker erection, and higher building valuation post construction build a strong case for this high rise structure to be executed in mass timber to a potential developer. A developer who choses to build in mass timber can see excellent return on investment, higher profits, and a positive impact in the fight against climate change.

CHAPTER 6

CONCLUSION

5.1 Findings

Out of this project, six key findings were made that should be considered in the design of mass timber structures.

Wood prefers to be loaded parallel to its fiber grain direction.

As a material wood is made from a bundle of fibers that run in one direction held together by a much weaker connecting material. As such wood is most strong when these fibers are fully engaged, and this weak connector material is not relied on for strength. Therefore, to best utilize the strength of the material and minimize failure members and forces should be aligned parallel to one another. Vertical compression loads should be transferred straight along columns and braces. Tension forces should pull straight on a wood tension member. Wood works moderately well in bending; therefore, traditional beams are perfectly acceptable in mass timber designs. However, the bearings of these beams should follow the loading parallel to grain principle.

Run columns continuously, do not bear on beam ends.

Along the same principles as previously mentioned forces should flow continuously through a column parallel to its fiber grain orientation. Demonstrated in section 4.3 the compression strength of wood is 9.7 times higher when aligned parallel to grain than not. However, a common practice, at least in light frame wood construction, is to transfer bearings through beam ends. Figure 60 diagrams this common occurrence and offers one solution to fix it. Often a beam might not fail under a midspan weight it carries but rather find its ends compressed as a point load is transferred through it. This causes crushing of the grains and leads to a potentially dangerous situation. A better solution, one used in the Origine Tower is to rest horizontal members on ledgers or metal hangers. This way there is no crushing force imparted on the beam and the load path of the column runs continuous without the need for extra reinforcement.

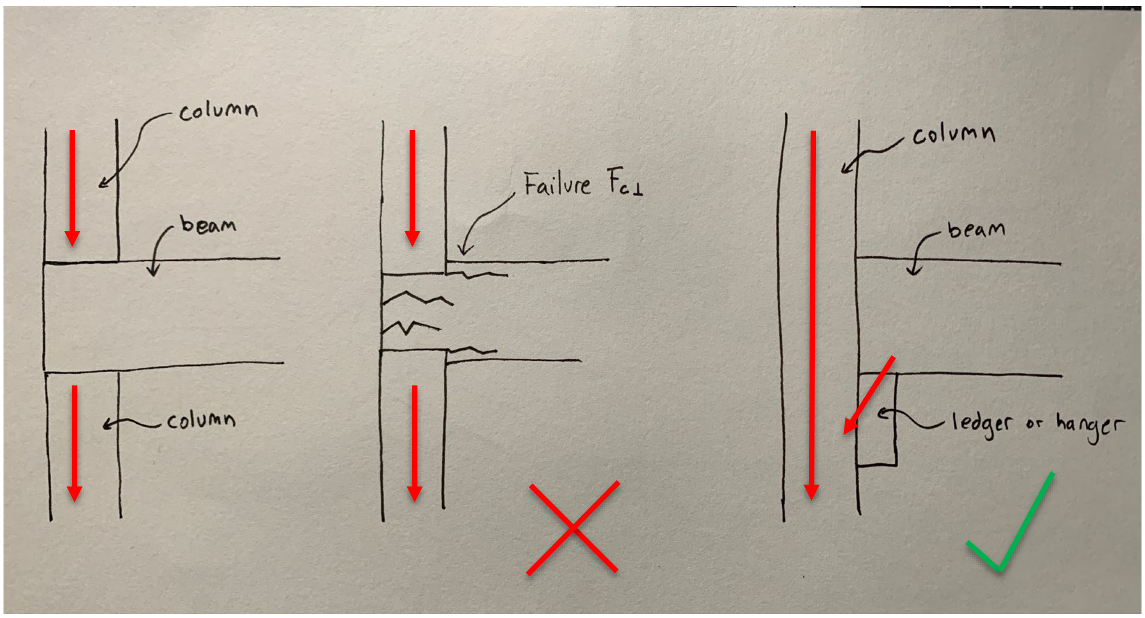

Figure 59- A common issue in light frame wood construction and one solution.

Regular grids and direct load paths to the ground are preferred in wood.

It comes as no surprise that a regular grid and direct load paths are more efficient. Wood timber framing is no exception. Many of the most exciting wood structures feature sculptural long spanning systems and in many cases the programming of the building demands it. When it is not needed though it invites challenges that wood can sometimes have trouble resolving. Complex, multidirectional, loads and high bending forces lead to larger and less economical systems. Ideally a load path should have a clear path parallel to component members' fiber direction to the ground. This is why the central core of the

Denver timber tower is made of straight members that move from inner column grids directly to the ground.

Use specific wood products matched to parts of a wood assembly.

A lot of modern mass timber projects use CLT as swiss army knife of construction. This practice of 'CLT-washing' isn't necessarily bad as CLT is a highly versatile and strong engineered wood product. Using CLT in every aspect of the building however is not the most efficient or economical approach to design. On its own CLT is very expensive with few manufacturers in North America. CLT is also a two way spanning panel and while great for diaphragms is not needed for purely liner load paths. The most efficient and economical way to build in mass timber is to use a mixture of engineered wood products where each type is most suited. Diaphragms can be made of CLT or NLT. Beams can be made from glulam or LVL. Columns can be glulam, LVL, or PSL. Light wall assemblies can be solid sawn wood studs. Matching product to use assures each aspect of the system is being 100% utilized and using a variety of less expensive stock EWP reduces material costs. For example, the exterior diagrid of the Denver tower is made from LVL. While glulam beams would be a functional option too, they are more expensive than LVL and not necessarily more effective than LVL in that application. LVL thus is the more efficient and economic choice. Inside the building large beams span 24' to carry the edges of CLT plates. LVL could be used here however, being not as strong as glulam the beams would need to be very large. These larger beams would cost more than the glulam option, and cost more to move given they would run heavier. Therefore, glulam is the logical choice in this section.

Diagrids are a good fit for mass timber structures.

Beyond the fact that visually diagrids are very exciting and dramatic they also are a good fit for tall mass timber structures. Diagrids use a lattice of small members to spread loading from multiple directions across its surface. The system puts low stress on individual members with this spreading action, a good fit for a material such as wood. The system is also redundant, if a single member fails the surrounding members take over. Diagrids transform incoming forces into pure tension or compression forces in their members. Following the principle outlined earlier, that the best practice in wood is to load it parallel to its grain, the diagrid again is a good match for wood construction. Finally, in general moment connections in wood are difficult to execute properly, a problem for a structure made from 90-degree joints. Because the forces between members of a diagrid enter the node as linear forces the connection at the node can be a simple steel plate.

Wood creates a lighter building; a lighter building makes simple foundations.

There is no question of whether a building made from wood is lighter than the same size building done in steel or concrete. This fact makes transporting materials to a site and hoisting them into place easier and less energy consuming. This fact also assisted this project in terms of how well it responded to its site. The tower sits near a retaining wall that prevents the river walk from caving in. While geotechnical engineering was not performed on this project two inferences were made; first the retaining wall would require some additional reinforcement. Second that process would become much easier in wood because the physical mass of the building would be far lower than a steel/concrete building. There would be less thrust generated by the tower pushing outwards on this retaining wall. While the soil conditions of downtown Denver are not poor other cities face serious issues in this regard. New Orleans is known for having poor bearing conditions for large structures. 18 story steel and concrete towers in this city need extensive and expensive bearing systems to save them from sinking into the ground. An 18 story wood structure however, with its lighter weight, could use a less serious bearing system. Origine Tower found a similar advantage in wood, poor soil bearing conditions were a key factor in the choice to make the tower out of wood.

Wood is an economically sound choice for investors.

Mass timber construction runs cheaper and quicker than steel construction. The material itself costs less, transportation to the jobsite is cheaper, and construction requires less labor and time. Post construction mass timber buildings have more value and can request higher rent from tenants than similar non-timber structures in the same market. Also, while not necessarily felt in a developer's wallet, choosing mass timber over steel or concrete is a huge benefit to the environment.

5.2 Carbon Impact of Project

The approximated impact of just the structural wood elements was calculated using the WoodWorks Carbon Calculator for Buildings. These values were acquired using a material volume takeoff list generated by Revit. The materials the program calculated for where only specified for the timber elements in the floor, columns, beams, and roof. The results are shown below in Figure 60.

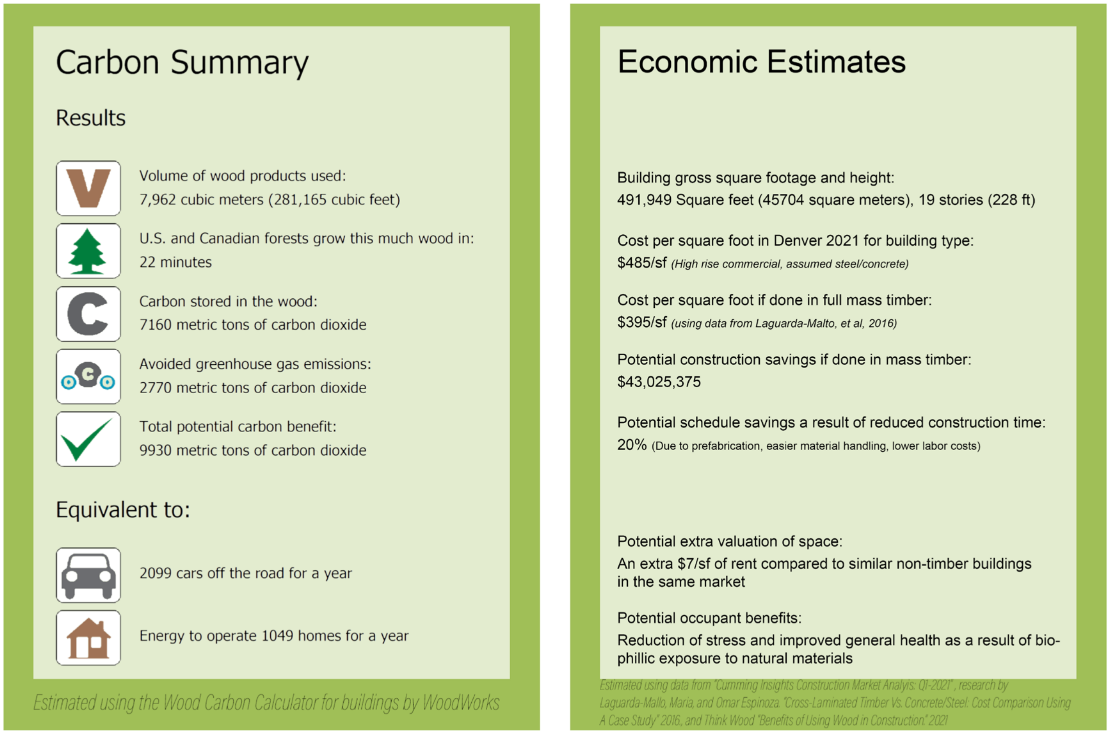

Figure 60- Approximate carbon results for the project. Calculated using the WoodWorks Carbon Calculator for Buildings. Also included, economic estimates of the project.

5.3 Final Thoughts

Beyond the findings of this thesis, there are other important strategies in wood construction that are worth discussing.

Show wood wherever possible.

Bio-philia, that is humanity's intrinsic love of nature, is an important consideration for all architecture. By allowing occupants to directly interact with wood, architecture can create a positive impact on occupants. As discussed, earlier studies have directly linked the visibility of wood to occupant health and happiness (Health Benefits of Wood, 2021). While fire considerations make this a tougher goal to achieve it is possible as can be seen by works such as the UMass Design Building.

Wear and tear considerations

Many wood species rot when they stay damp for extended periods of time. Yet one of the major aspects of the design of this building is expression of its materiality, even on the exterior. There are options to daylight wood on the exterior of building and avoid rot. One is to use rot resistant species such as cedar. While cedar itself isn't as strong as some other species it can be used as a cladding over vulnerable wood components and still make the statement "I am wood." Another strategy is to use wood fiber laminate cladding, a composite of wood and other chemicals that creates a weatherproof panel that retains its wooden appearance.

Inside the building, again wood faces wear and tear from occupants. There are two schools of thought regarding how to treat this. One is to leave it exposed and let it happen and one is to cover it up. The arguments for exposure are philosophical; architectural theorists have posited that showing signs of wear and tear gives a building a deeper soul by showing that it is lived in. There is also the theory that tenants of an apartment, when given nicer quality materials, treat the space more respectfully. Architects of college dorms in recent times have applied this theory to student housing, which is damaged at higher rates than other housing. On the other hand, mass timber elements with cosmetic damage are very difficult to restore. If someone carves into a wood column the wood is forever damaged, the options to fix it being to fill it or cover it. Cladding the wood in gypsum wall board offers protection to the wood, and this layer can be replaced very easily. In doing this the system can also gain fire code approval easier.

This system however would hide the materiality of the building and dilute the bio-philic benefits of the architecture. In the end the only answer this thesis can provide is a testimony of the UMass Design Building. Its members are left exposed to thousands of college students year after year and yet there is little to no apparent defacing or damage to the building.

Fire code is catching up.

As of the 2021 IBC Code larger buildings are now possible in timber. Figure 61 illustrates the new building types possible:

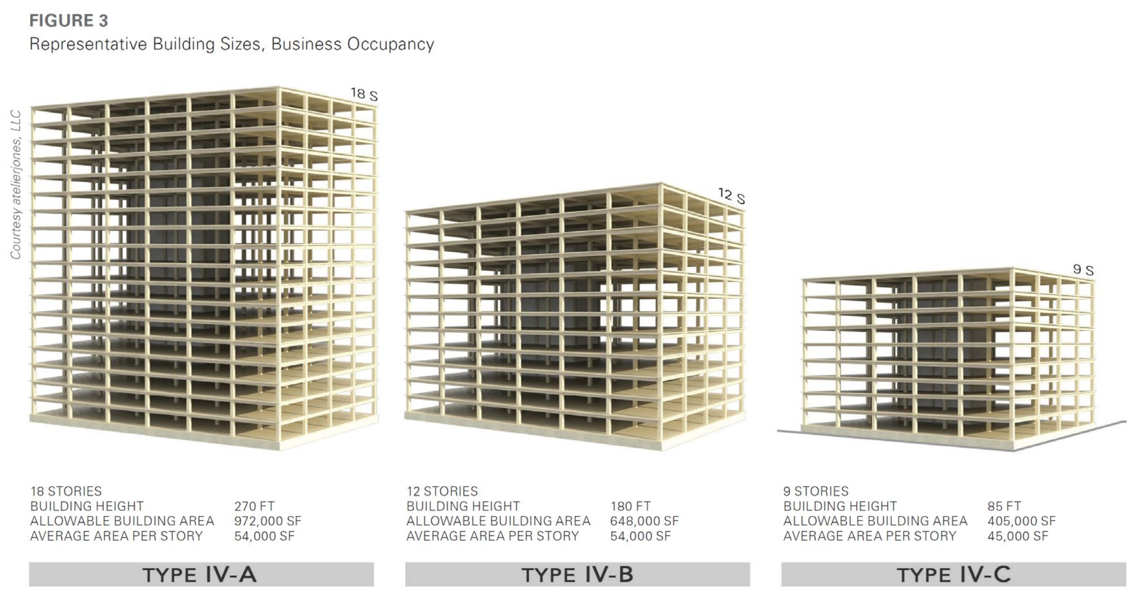

Figure 61- Updated fire code allows for these building types.

At 228 feet tall, 18 stories, an average area per story less than the given maximum, and a total gross square footage of 491,949 sq.ft. it is completely possible to create the project this thesis proposes as Type IV-A building in the new fire code. To be considered a Type IV-A building all structural wood would need to be covered by noncombustible material such as gypsum wall board. 80 minutes of protection on this inside, 40 minutes on the outside, an inch of protection on floors and ceilings, and 80 minutes encasing shafts would be the required noncombustible protection with no exceptions ("Tall Wood Buildings in the 2021 IBC"). This is a very reachable goal; two layers of gypsum wall board already provide 2 hours of protection and don't take up an enormous amount of space. By not increasing member sizes to incorporate a sacrificial wood volume, members can stay small and interior spaces large. While sprinklers are not yet required, they are proposed to be required and realistically should be installed.

Building this structure as Type IV-A would answer the previous question of covering wood surfaces to protect wear and tear by removing the option to leave them exposed. Unfortunately, the building would have a much harder time expressing its materiality because it cannot show the wood structure. In addition, it is not certain what the economic and environmental impact of cladding all members in GWB would have. Would they offset the benefits the wood provided?

Wood architecture and concrete can look similar, with some caveats.

At the beginning of this thesis one of the questions asked was whether wood architecture was just mimicking concrete or if it chose this form itself. Concrete architecture uses plates, posts, and beams. It also uses prefabricated elements. Modern wood architecture does the same things. Does wood want to be in this form? Yes, with certain stipulations.

This theoretical project designed the ideal wood structure in terms of its needs as a material. The question was asked however, if it could take another form, and the answer was yes. It has been shown with success that wood can be made in a plate, post, and beam arrangement as shown in Figure 62.

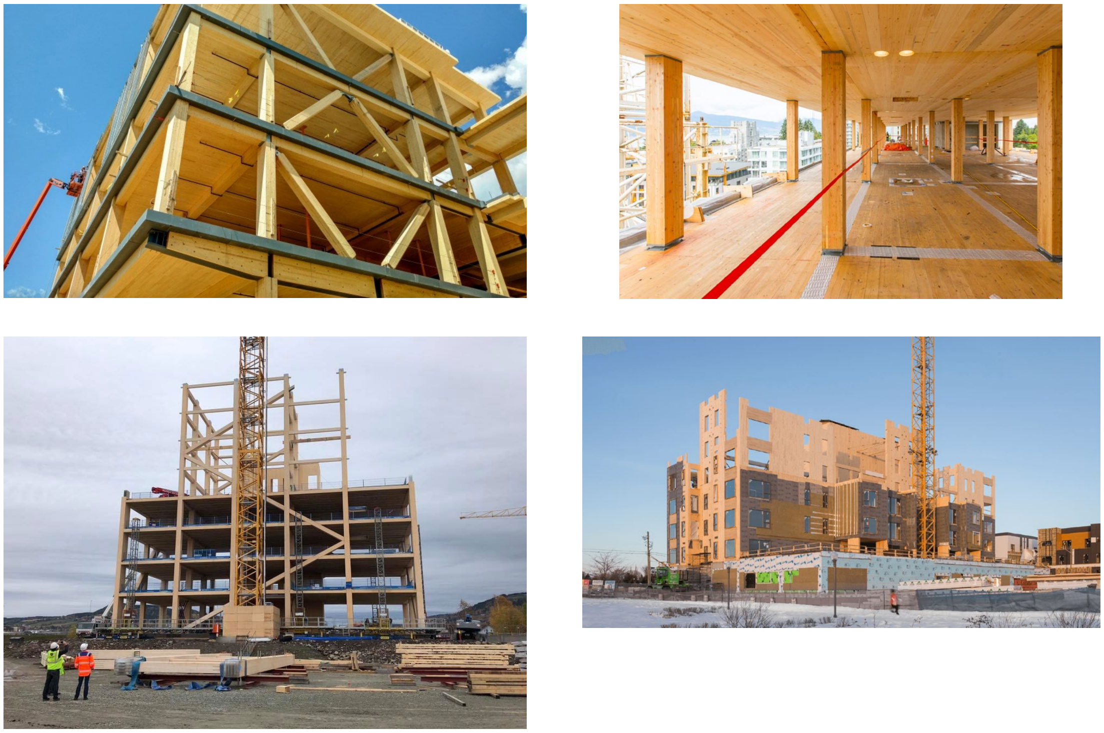

Figure 62- (Left to right) UMass Design Building, Brock Commons, Mjøstårnet, and Origine all in construction.

All four buildings shown were used as precedents for this project and all follow in some way a plate, post, and beam arrangement that can be seen in concrete architecture too. All four of these projects are major successes, showing that this form does work in wood. However, the key difference between wood and concrete in this form is the lateral stability question. Wood requires more extensive lateral support as it is lighter and more susceptible to wind and earthquakes. The UMass Design Building and Mjøstårnet use large diagonal members to counter these forces. This is very effective and creates an open façade but unfortunately the diagonal members create odd moments when they transect rooms and windows. Brock Commons uses a concrete core; therefore, it is not a pure wood building but is still successful. Origine uses CLT plates arranged strategically with many shear walls, concrete sometimes does this too and it works for both.

The project this thesis proposed, if done in a way similar to these projects, would likely have the large diagonal members instead of the diagrid. This system would have worked. It was not chosen though because of its potential interference with the units. These members might have left many undesirable units in their wake, a less than acceptable circumstance for an apartment building. Figure 63 shows the odd moments that formed in parts of the UMass Design Building as a result of large diagonal members. As seen the beams cross the window and the back wall. Students, as well as the writer of this thesis, have been observed hitting their heads on the beam when leaning back in their chairs or picking up backpacks left under the beam. The TV can only be a certain size and fit in a certain place because of the diagonals on the wall.

Figure 63- Odd moments with diagonal wood members in the UMass Design Building.

The design proposed in this thesis eliminates these moments by bringing diagonal members outside, as well as arranging them to not block windows.

Conclusion

Mass timber construction is an exciting form of architecture that can greatly reduce the negative impact of construction on our environment. We are still developing an architectural language for this emerging technology. We are still learning what is successful and perhaps what is not. The nice part about mass timber is that it is somewhat form forgiving. It is highly versatile and accepts many different forms. This thesis proposed one way that it argues is the most efficient. However, the options are not limited to just this form and it will be exciting to see what these next few years produce in wood architecture.

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